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The effects of process parameters on elements of appearance for an automotive coatings process.

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THE EFFECTS OF PROCESS PARAMETERS ON ELEMENTS OF APPEARANCE FOR AN AUTOMOTIVE COATINGS PROCESS

by

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ABSTRACT

This research investigated the effects of topcoat process parameters on the appearance of automotive vehicles. From preliminary screening, it was identified that clear coat thickness, booth humidity/temperature, dehydration solids, bell and reciprocator flow rates and reciprocator fan air had the most impact on the appearance. Analysis of previous experiments indicates that increasing clear coat film thickness improves appearance, with some exceptions and limitations.

A fractional factorial two-level DOE matrix was created to test the impact of five identified variables on appearance. The panels were sprayed with waterborne base coat followed by solventborne clear coat and measured with an appearance measuring instrument.

Dehydration solids were found to affect all appearance elements and all other process parameters affected at least one appearance element. In general, to improve appearance, it is necessary to increase dehydration solids, clear coat film thickness and reciprocator fan air and/or decrease bell flow rate and reciprocator flow rate.

To Mom and Dad for their love and support.
To Dan for his patience and encouragement.

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CHAPTER 1 – INTRODUCTION

1.1 Automotive Paint Processes

The automobile has quickly become an integral part of everyday life. According to Statistics Canada (2006), of an estimated 12,343 households surveyed, almost 90% reported ownership of at least one vehicle – 37% of households reported owning one vehicle and 52% of households reported owning two vehicles. In addition, over 300,000 new vehicles were sold in Ontario alone in 2004 (Statistics Canada, 2005). With the choice of vehicles available for sale in today's market, style and quality are important considerations for the consumer in the decision-making process.

The paint finish of a vehicle plays a major role in how customers perceive a vehicle's quality. Attention to exterior detail suggests to consumers that interior assembly has received the same consideration. Perception of appearance is highly dependant on personal opinion and experience. For most, the ideal look is mirror-like: highly glossy and perfectly smooth. Inspection techniques must be stringent to ensure that high quality finishes are being produced. Quality control by visual analysis is insufficient as it is highly subjective. In addition, evaluation conditions are often not clearly defined. To develop a credible and consistent means of evaluating appearance, it is essential that subjective "opinion" be replaced with objective "data" (Perceptron, 2003). Currently, there are several appearance-measuring instruments, each employing a different measurement technique.

The use of a qualitative instrument helps to avoid appearance problems in two ways. First, it detects poor appearance in final vehicle finishes, preventing poorly finished vehicles from being delivered to customers. Even more importantly, the instrument's measurements (mathematical representations of appearance elements) can potentially be related to process data. As appearance variation is indicative of process variation, this information can be used to perform statistical and analytical evaluations enabling the optimization of quality-control systems. Finding and eliminating causes of variation in painting processes leads to better appearance, fewer defects and reduction of the environmental burden through avoidable re-work, scrapped parts and wasted paint. In addition, numerical evaluation enables better matching of fascias and other parts which are added to the vehicle after it passes through the paint shop. Finally, quantitative evaluation enables the detection of subtle variations in the process which can be corrected before the problem becomes noticeable.

Vockery (2004) estimates that approximately 90% of emissions released during the manufacture of a vehicle are due to the paint process. Traditionally, paint pigments and resins were applied to a vehicle using organic solvents as conduits. Solventborne coatings are known to provide excellent corrosion protection, hardness and gloss. However, they are responsible for the majority of the emissions released during the painting process. As technology progresses and environmental regulations become more stringent, DaimlerChrysler is turning to "environmentally friendly" solutions. Mancina (2005) reports that while nearly 50 % of all basecoats used in the automotive industry are waterborne, which indicates that the solvent used to carry the paint pigment is primarily composed of water, only 3 of DaimlerChrysler's 12 manufacturing facilities use solventborne material. The use of waterborne coatings has required a compromise in overall quality compared to solventborne coatings (Brandau, 1990). The research and development of new coatings technologies and viable cost-effective application techniques continue at the current time. As a result, the automotive industry is torn between trying to reduce costs and maintain high performance and reduce environmental burden (Tullo, 2002).

Mancina (2005) estimates that it costs DaimlerChrysler $600 USD to paint a vehicle. In addition, he estimates $3 USD/unit sold in paint related warranty problems. The costs associated with this process, combined with the negative impacts this process has on the environment, encourage automotive manufacturers to coat the vehicle correctly on the first attempt.

1.2 DaimlerChrysler Layering Process

A vehicle undergoes many processes as it travels along the conveyor in an assembly plant. Each process contributes to the overall function and quality of the vehicle. Of all these processes, the paint process is the most complex and time-consuming. In addition, the paint process is a very costly process, both to the manufacturer and the environment. At DaimlerChrysler, six coating layers are applied. Figure 1 illustrates the layering process. Each layer in the coating process has a unique function. Beginning at the surface of the vehicle body, the zinc coated steel is treated with phosphate. The purpose

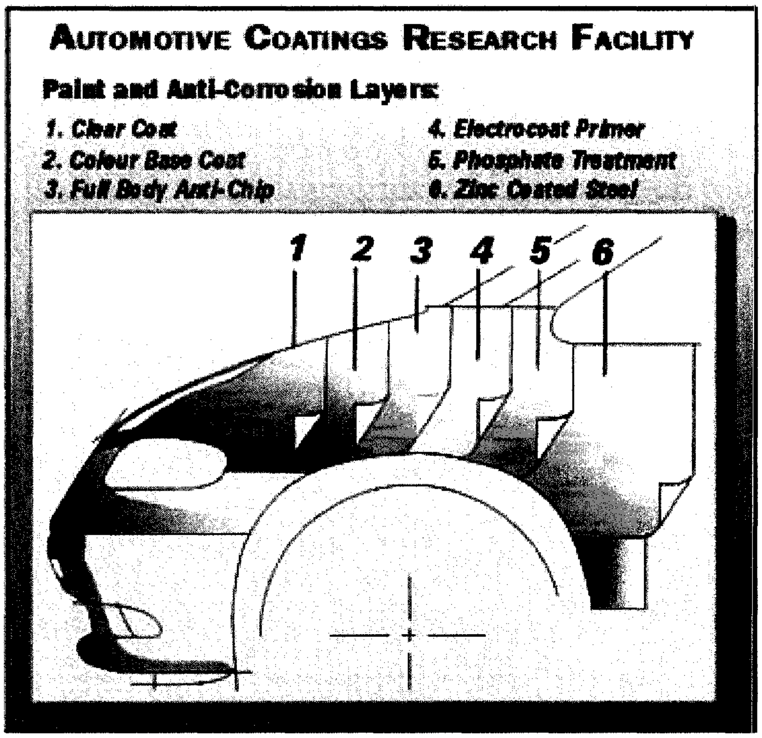


Figure 1 – DaimlerChrysler coatings layering system. Reprinted with permission from Mancina (2005)

of the phosphate layer is to clean and chemically treat the vehicle bodies. The zinc phosphate coating promotes adhesion of electro-coat primer, the second layer, to the steel and enhances corrosion protection. The electro-coat layer, or e-coat layer, also aids in corrosion resistance of the steel body. The third layer, the full body anti-chip primer, is employed to improve resistance to chipping. Above this layer lies the base coat layer, which is added for colour and provides protection from UV light. Finally, the top layer, clear coat, is applied to the vehicle to enhance durability and shine.

1.3 General Automotive Coatings Research Facility Process Flow

A schematic of the process flow at the University of Windsor/DaimlerChrysler Automotive Coatings Research Facility is provided in Figure 2. This facility is capable of coating materials of various sizes ranging from small metal panels to full sized vehicles using a combination of powder, waterborne and solventborne coatings. Prior to entering the paint shop, the vehicle is pretreated to cleanse the body of oils and greases. The vehicle is loaded onto the inspection deck where it is prepared for the first of the three topcoat layers – primer. After preparation, the vehicle travels along either the powder conveyor (indicated by the blue line) or along the liquid conveyor (indicated by the green line) depending on the type of primer used. Powder primers are applied with the powder robots, solventborne primers are applied with the clear coat bells and waterborne primers are applied with the base coat bells. A bell is a rotating cup along which the paint flows until it reaches the edge where it atomizes. After being primed, the vehicle moves down the oven conveyor (indicated by the red line) where it is cured and cooled. The vehicle again stops at the inspection deck where it is sanded to remove dirt and other defects before proceeding through the liquid colour line. A layer of base coat is applied in two coats before the body passes through a dehydration zone which removes some of the water and solvents from the applied base coat material. The first coat is applied electrostatically using bells while the second coat is applied using conventional non-electrostatic spray guns. Finally, a layer of clear coat is added. A period of ambient flash time follows the application of clear coat while the vehicle travels from the clear coat spray booth to the entrance of the oven. The vehicle is cured in the oven before leaving the paint shop. The first two zones in the curing oven are black wall radiators which minimize the travel of dirt to the drying coatings. The third and fourth zones are convection zones which are used for uniform cure. These zones maintain the metal temperature at the specified cure temperature.

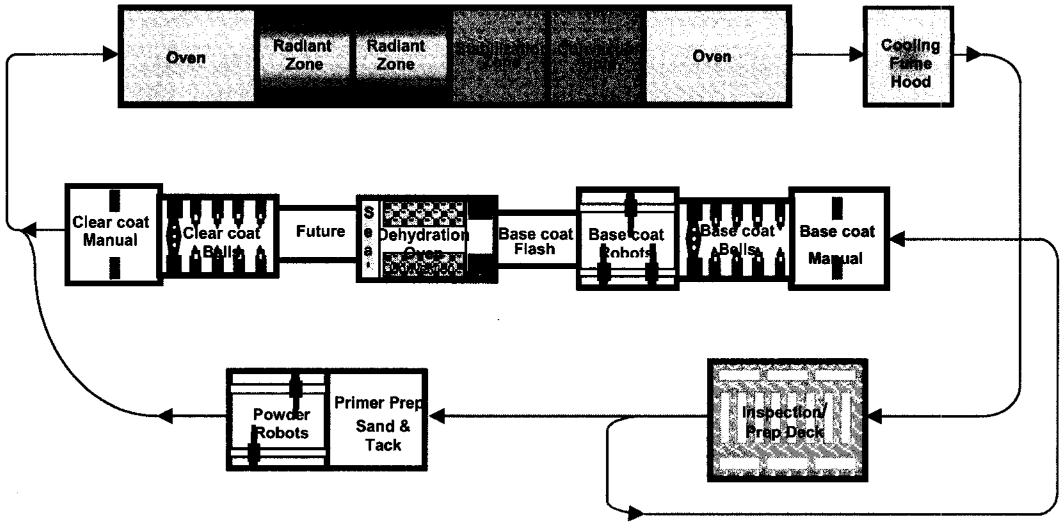


Figure 2 – ACRF process flow diagram. Reprinted with permission from Mancina (2005)

1.4 Objectives

There are many variables involved in the process of coating a vehicle, beginning with the makeup of the paints and solvents, through the application of the paints with electrostatic and non-electrostatic equipment and ending with the final cure of the paint in the oven. Each of these variables has the potential to impact the overall appearance of the vehicle's finish. The objective of this thesis is to relate some elements of appearance to various topcoat paint process parameters. It is hoped that a better understanding of these relationships will result in an optimization of the process and increased knowledge of parameters affecting appearance.

1.5 Scope

The experimentation for this study was completed at the DaimlerChrysler Automotive Research and Development Centre (Windsor, Ontario). The process parameters investigated were limited to those involved in the application of the topcoat layers. The experimental panels were coated under extreme conditions which can be reasonably expected to occur at DaimlerChrysler assembly facilities. Consideration was given to maintaining constant base coat film thickness as process parameters were varied and was rejected due to the complexity it would bring to the experimentation and the unlikelihood that it would be controlled at DaimlerChrysler assembly plants. The measured surface quality in these experiments will be analyzed for correlation to application process parameters.

The scope of this thesis included:

1. Measuring the appearance of painted pre-production test panels and statistically correlating the appearance elements to process parameters. This will determine which process parameters have an influence on appearance and therefore require further investigation.
2. Searching the ACRF archives for tests which measure the effect of different process parameters on appearance elements and analyzing the data.
3. Performing factorial experiments to determine the effect of significant parameters uncovered in 1 which were not already tested in 2.

CHAPTER 2 – LITERATURE REVIEW

2.1 Development of Appearance Comparison Techniques

Historically, appearance was judged using visual assessment. In 1980, Advanced Coatings Technology (ACT) Laboratories Inc. (Hillsdale, USA) developed a set of ten orange peel panels (orange peel is defined as the appearance of irregularity of a surface resembling the skin of an orange (Behr, 2004)) and to be used as a standard for appearance comparison and to facilitate visual assessment (Lex, 2004). The panels were simply labeled 1 through 10, with panel 1 having a high degree of surface roughness and panel 10 having a smooth finish. Although these panels were used as standards, a standard procedure with illumination and viewing conditions was not defined. It was later found that there was no gradation in the overall appearance of these panels and there was poor reproducibility between panel sets over the years (Daws, 2005). Aspects of appearance other than orange peel, such as gloss and distinctness of image (DOI), were not well controlled even though a combination of these characteristics was used to evaluate appearance. In addition, although expert inspectors can be effective at assessing perceived appearance; it can be labour intensive, time consuming and subjective.

Over time, companies began to realize the importance of mechanical evaluation of appearance and as a result, appearance measuring instruments were developed. In comparison to visual evaluation, optical techniques are robust and objective, but not always effective in assessing perceived surface appearance (Scheers *et. al.*, 1998), since the measurements are physical in nature. Consequently, appearance values must be defined via correlative studies (Tannenbaum, 2000). Several such studies have been completed, which correlate painted appearance panel samples to various appearance measuring instruments. In general, the results of these studies remain proprietary information for the company that funded them. One study was conducted by Giroux (2003) which involved correlating black panels with various primer film thicknesses to the measurement parameters used by three appearance measuring instruments – Perceptron Autospect, BYK Gardner wave-scan Plus and BYK Gardner wave-scan DOI.

Sixty people valued the panels in order of decreasing appearance. These values were analyzed using various statistical techniques. It was concluded that the wave-scan DOI's measurement parameters most closely represented human perception.

2.2 Automotive Coatings Materials

Paint is a pigmented coating layer on a substrate that is applied by brush, spray or other techniques (Brandau, 1990). All paints consist of the same basic components which include the vehicle (resin binder), solvent, pigment (except in clear coat) and additives. Spray coating, the technique used in most manufacturing facilities, is the fastest method of applying paint. This technique is extremely versatile because it is fast drying, it has a unique ability to coat irregularly shaped surfaces and it generally yields a high quality, smooth and uniform coating. Three types of spray coating are currently in use in manufacturing facilities: air spray, airless spray and electrostatic spray (Brandau, 1990). At DaimlerChrysler, air spray and electrostatic spray techniques are utilized in the paint shop. The air spray technique uses a spray gun which atomizes paint by mixing it with compressed air. The fine spray produced is projected onto the substrate. Often, this technique leads to overspray (sprayed paint which does not adhere to the vehicle), which results in a waste of paint. Electrostatic spray uses atomizing equipment (either bells or discs) and provides an electrostatic charge to the paint particles as they are applied to the substrate. Electrostatic forces are strongest at the coating-surface interface (Baghdachi, 1996). After application, the coating and the surface contain some residual electrical charges and the interaction between these charges accounts for some adhesion. This technique has many advantages over air spray, but is limited to conductive substrates since the object to be painted must be grounded to attract the positively charged paint particles. Electrostatic application results in reduced overspray since the paint is attracted to the substrate. In addition, a uniform film thickness can be realized as the applied paint acts as an insulator which reduces the attraction of the paint at that point as it builds up (Brandau, 1990).

Rheology is the science of the flow and deformation of materials experiencing an applied force (Vincent, 2004). In automotive coatings, the applied force is the pumping or spraying action formed when the coatings are applied. Automotive coatings are subjected to extremes during their manufacture, application and cure. As a result, the properties of these materials must be robust under a wide range of rheological conditions.

Viscosity is a major determinant in how well paint will settle during storage, flow out of the can, spray and resist dripping during application and flow during drying. For waterborne coatings, the viscosity changes with changing shear stress. Many coatings used in the automotive industry are thixotropic in nature and exhibit a decrease in viscosity as a function of time. These materials will recover all or most of their original viscosity when the forces acting upon them are removed (Vincent, 2004). As a result, paint becomes less viscous when it is agitated and returns to its original state at rest.

As paint is applied to a substrate, the solvent begins to evaporate and the paint begins to dry. As time passes, an increased amount of solvent will evaporate until the paint has dried completely. With most paints, air drying allows the solvent in the paint to evaporate, leaving the pigment and the resin unchanged on the substrate. Due to time constraints, space limitations and contamination concerns, air drying is not an acceptable alternative for most industrial processes. Heat is used to speed up the curing process by forcing the solvent to evaporate more quickly. In addition, as the paint is heated, the molecules of resin in the paint begin to flow together. This facilitates molecular cross-linking which improves the adhesion to the substrate and results in improved chip resistance, durability and overall finish quality. Although curing paint with heat is more advantageous than air drying, the process must be monitored to prevent defects in the appearance such as solvent pops, blistering and colour damage (Haden, 1998).

The paint curing process is dependant on time, temperature and air flow (Haden, 1998). For paint to cure, the substrate must be heated to a certain minimum temperature. Once the temperature has been reached, it must be maintained for a specified amount of time.

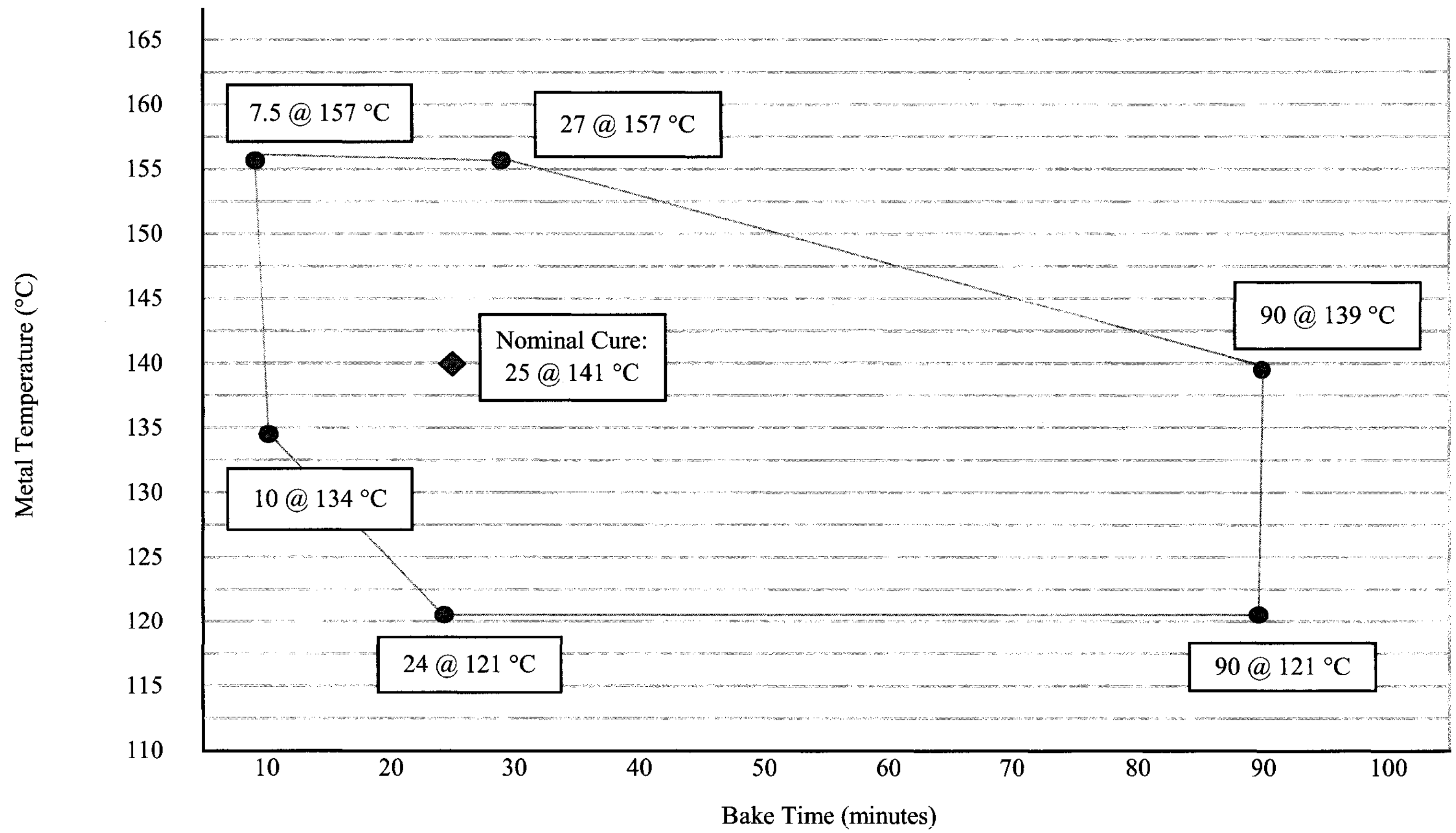


Figure 3 – Generic cure window

This information is provided by the paint manufacturer in the form of a cure window. This window identifies time and temperature combinations that will yield the proper cure. In addition, the nominal cure conditions are identified. For this thesis, the nominal conditions were used. A generic cure window is found in Figure 3.

2.3 Surface Structures and Appearance

In general, appearance can be defined with two characteristics – waviness and brilliance. These characteristics can be seen by looking at a painted surface in two very different ways. If you focus on the surface, you will acquire information about the waviness characteristic. Specifically, you will obtain information about the size, depth and shape of surface structures (Fensterseifer, 2004). Surface structures are formed through the deposition of paint particles on the surface of the vehicle. Each layer of paint requires the application of a steady stream of these paint particles and as the particles are sprayed, they align themselves relative to each other in groups or structures.

When a painted surface is illuminated, light is reflected in different directions, depending on the slope of the structure element. Only elements reflecting light in the direction of our eyes are perceived as light areas. As a result, our eyes perceive waviness as a pattern of light and dark areas. The contrast within a structure gives us the impression of the depth of the structure and indirectly, the waviness of the surface is evaluated. This principle is illustrated in Figure 4.

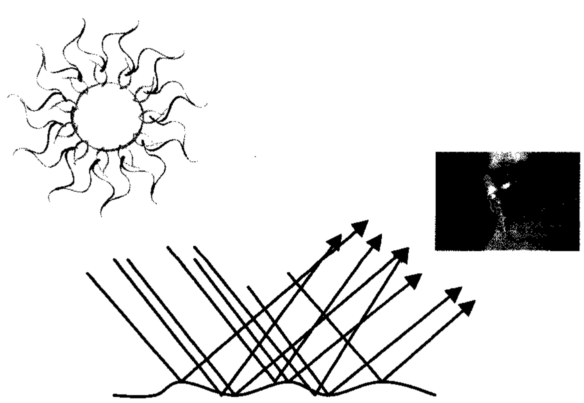
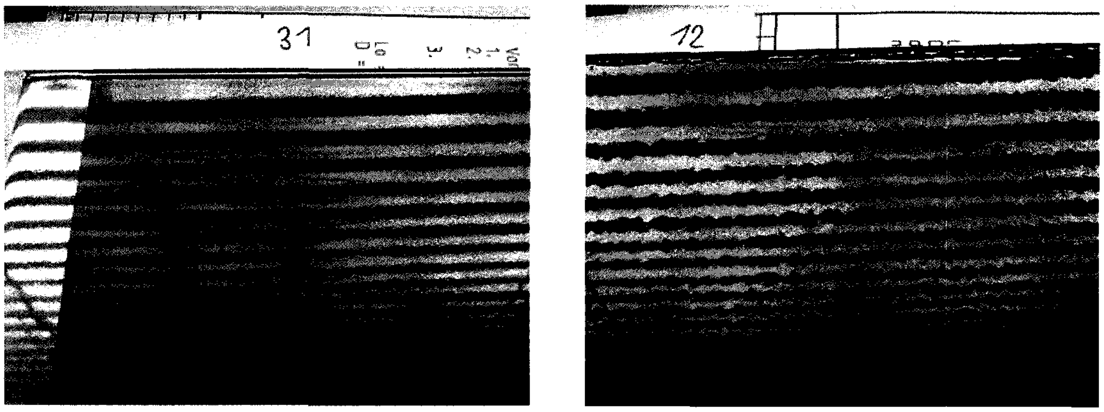


Figure 4 – Human perception of waviness

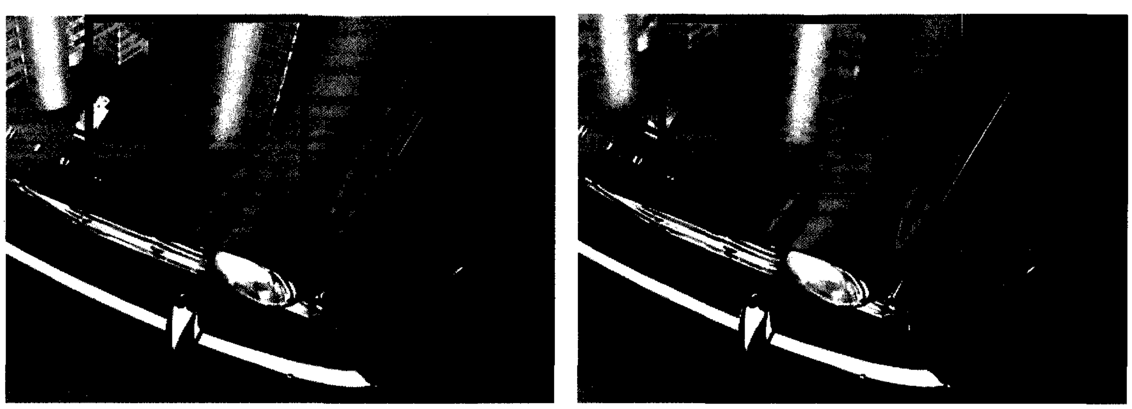
In addition, the size of the structure plays an important role in the appearance of the surface. Figure 5 shows how humans visualize surfaces with small and large structures.



Small Structures (5a) Large structures (5b)

Figure 5 – Perception of small and large structures. Reprinted with permission from Harry Bunkowski, BYK Gardner (Geretstried, Germany).

Focusing on the reflected image of an object allows one to obtain information about the image forming qualities, also called brilliance or distinctness of image (DOI), of the surface (Fensterseifer, 2004). The lines of the image will either appear distinct or blurred. If the outline of the image appears distinct, the reflected light source will look brilliant. However, if the outline of the image is blurred, the reflected light source will look diffuse. Figure 6a is an example of a distinct image, while Figure 6b is blurry.



Distinct Image (6a) Blurry Image (6b)

Figure 6 – Image forming quality of a surface. Reprinted with permission from Harry Bunkowski, BYK Gardner (Geretstried, Germany).

2.4 wave-scan DOI Appearance Measurement Principle

The wave-scan DOI is an appearance measuring instrument developed by BYK Gardner (Geretsried, Germany). It is a relatively new instrument on the market and BYK Gardner representatives maintain that it is able to simulate the human eye's resolution at various distances by dividing the measurement signal into several ranges. As stated earlier, Giroux (2003) found that the wave-scan DOI's measurements correlated well with human perception. This instrument was used to capture the appearance information for this project.

In general, appearance depends on the distance of the painted surface to the observer and the resolution of the observer's eyes (Lex, 2004). Figure 7 illustrates this principle. At short distances, humans can see appearance structures with short wavelengths. Conversely, at far distances humans can see appearance structures with long wavelengths. BYK Gardner (2002) maintains that appearance structures ranging in size from 0.1 mm to 1.0 mm can only be seen at distances of 40 cm or less. Longer wavelength structures (0.8 mm – 100 mm) can be seen at distances between 1 m and 3 m. Very fine structures (<0.1 mm) which cannot be resolved by the human eye are not recognized as a pattern of light and dark, even at a very close distance.

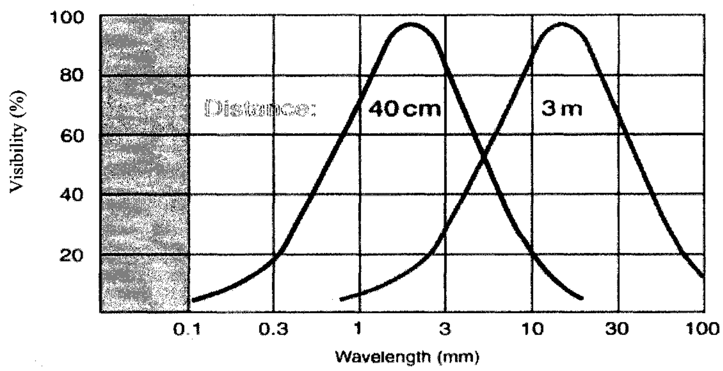


Figure 7 – Relationship between distance and resolution of the human eye. Adapted from BYK Gardner (2002)

The wave-scan DOI uses a laser point source to illuminate the surface of the sample at a 60° angle. The instrument is rolled along the painted surface and takes a reading every 0.08 mm for a total of 1250 measurement points over a distance of 10 cm. A detector measures the reflected light intensity at each point. In this way, the optical profile of the surface is detected. An overview of the wave-scan DOI's measurement principle is provided in Figure 8.

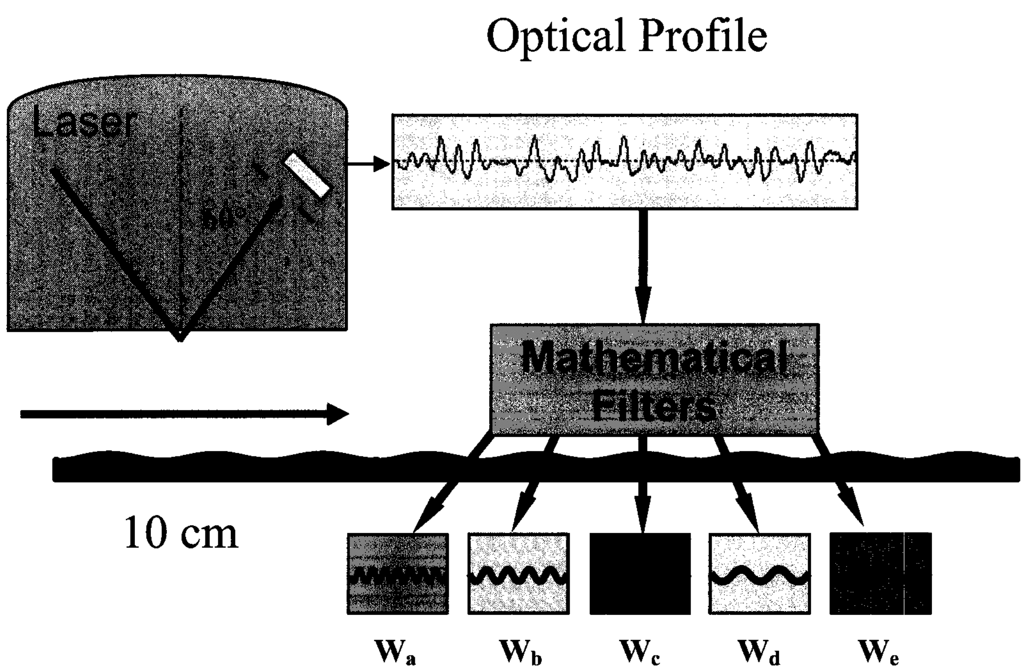


Figure 8 – wave-scan DOI instrument principle. Reprinted with permission from Harry Bunkowski, BYK Gardner (Geretstried, Germany).

The step-wise development of the optical profile is illustrated in Figure 9. At point 1, the laser reflects off the surface and directly onto the receptor. Point 1 represents a plateau on a peak on the surface and translates into a peak on the light intensity profile. At point 2, the laser reflects off the surface at an angle and not directly into the receptor. Point 2 represents a down slope on the surface profile that translates into a valley on the light intensity profile. Finally, the laser reflects directly into the receptor at point 3. This point represents a valley on the surface profile and translates into a peak on the light intensity

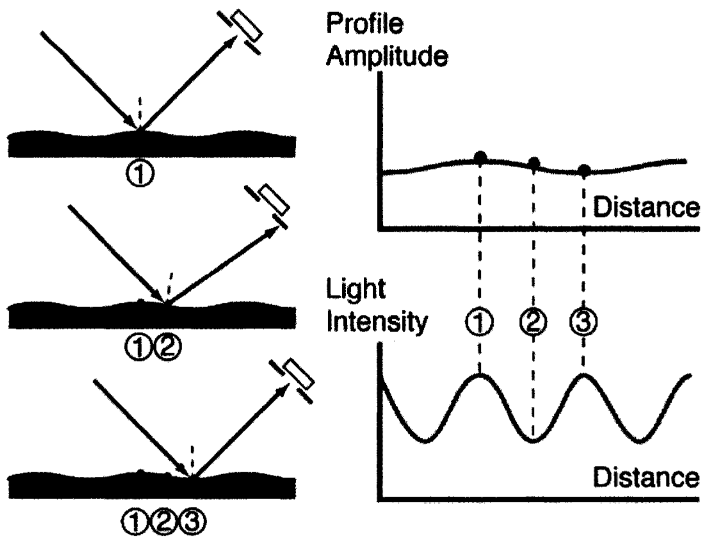


Figure 9 – Development of optical profile. Reprinted with permission from Harry Bunkowski, BYK Gardner (Geretstried, Germany).

profile. In this way, the light intensity is measured point by point along the scan pathway of the instrument (BYK Gardner, 2002).

Mathematical filter functions, in particular Fourier transforms, are used to divide the optical profile into five wavelength ranges. Table 1 summarizes the five wavelength ranges. Wa and Wb are considered shortwaves, while Wc, Wd and We are considered longwaves.

Table 1 – Summary of wavelength ranges measured by the wave-scan DOI

Wave-scan Element	Wavelength Range
Wa	0.1 mm – 0.3 mm
Wb	0.3 mm – 1.0 mm
Wc	1.0 mm – 3.0 mm
Wd	3.0 mm – 10.0 mm
We	10.0 mm – 30.0 mm

Within each wave-scan element, the light intensity profiles are standardized by assigning a value of 1000 to the average. The absolute value of the deviations of each individual point to the standard line are averaged to obtain a contrast value, where

$$Contrast = average|x - 1000|$$

Ultimately, the profile data is simplified to a single contrast value for each element. The contrast values for each of these elements range from 0 to 100. The surface waviness will decrease with lower values of contrast. For example, if each of the optical profile points fell along the average line of 1000, the contrast would be equal to zero – a perfectly smooth appearance. The wave-scan DOI values produced by measuring a glass panel, whose appearance is close to ideal, will yield contrast values approaching zero for each of the wavelength ranges.

In addition, the wave-scan DOI instrument is equipped with a reflectometer which measures reflected light intensity and characterizes brilliance, the other important factor in measuring appearance. A white light emitting diode (LED) illuminates the surface of the sample at a 20° angle. The reflection is captured by the lens of a charge-coupled device (CCD) chip. The dullness measurement technique is illustrated in Figure 10.

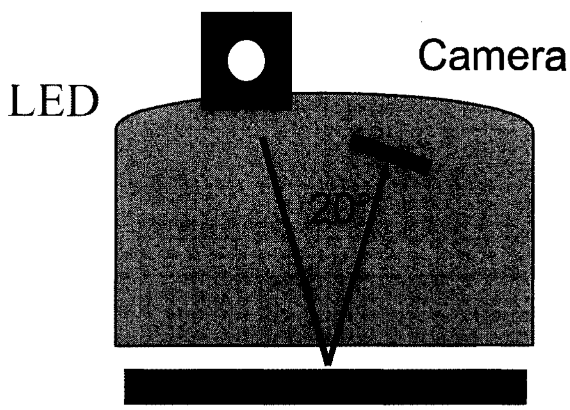


Figure 10 – wave-scan DOI reflectometer. Reprinted with permission from Harry Bunkowski, BYK Gardner (Geretstried, Germany).

The intensity of the scattered light at the edges of the image of the LED in relation to the intensity at the centre produces a value called dullness.

$$\frac{I_{scatteredlight}}{I_{centre}} = \frac{scatter\ value}{max} = dullness$$

Brilliance or DOI is influenced by structures smaller than 0.1 mm where diffuse scattering of light reduces the contrast and results in a reduction in gloss. It is also influenced by structures between 0.1 mm and 1 mm, which distort the edges and cause outlines to become blurry. As a result, DOI is a function of dullness and wavelength ranges Wa and Wb.

$$DOI = f(du, Wa, Wb)$$

Similar to the structure spectrum, DOI is measured on a scale of 0 – 100. However, in contrast to structure spectrum elements, a higher value indicates better DOI.

In addition to the six values measured by the wave-scan DOI, two calculated values are often reported – longwave coverage and wet look. Longwave coverage (LC) describes how well the short waves can mask the longer waves and is found using Equation 1a. The wet look (WL) describes the glossiness of a surface coating and is calculated using Equation 1b. Longwave coverage and wet look relationships are illustrated in Figure 11.

(1a) $$LC = 100 * \frac{(Wb - Wd)}{(Wb + Wd)}$$

(1b) $$WL = 100 * \frac{(Wc - Wd)}{(Wc + Wd)}$$

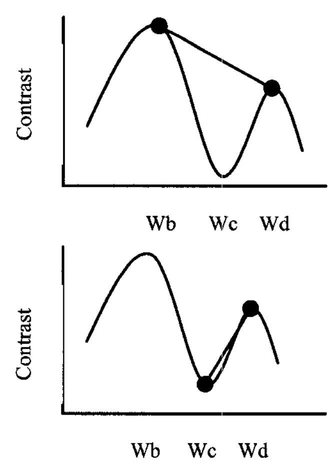


Figure 11 – Longwave coverage (LC) and wet look (WL)

BYK Gardner, the makers of the wave-scan DOI, previously manufactured an instrument called the wave-scan Plus. This instrument used the same principle as the wave-scan DOI to measure appearance; however it was capable of measuring a smaller range of structures. The instrument's output consisted of two values: SW (shortwave - 0.3 mm – 1 mm) and LW (longwave - 1 mm to 10 mm). A comparison of the elements measured by wave-scan plus and wave-scan DOI is provided in Figure 12.

wave-scan DOI

du Dullness	Wa 0.1 - 0.3 mm	Wb 0.3 - 1.0 mm	Wc 1 - 3 mm	Wd 3 - 10 mm	We 10 - 30 mm
		Shortwave 0.3 - 1.2 mm	Longwave 1.2 - 12 mm		

wave-scan Plus

Figure 12 – Comparison of wave-scan Plus and wave-scan DOI measured elements

The limitations in the ability of the wave-scan Plus to measure short waves, which are important in the assessment of DOI, resulted in the development of a more advanced instrument – the wave-scan DOI.

2.5 Ideal Structure Spectrum

Lex (2004) claims that appearance depends on the distance of the observer to the viewing surface and the resolution of our eyes. At a short distance smaller structures are visible, while at a further distance, large structures become visible. Lex (2004) states that at 40 cm, the human eye is capable of discerning structures which are 0.1 mm to 20 mm in length and at 3m, structures ranging in size from 0.8 mm to 100 mm can be seen. For this reason, the ideal structure spectrum is designed such that a minimum value occurs at W_c whose structures range between 1.0 mm and 3.0 mm. In this range, surface structures are best resolved at 40 cm distance (see Figure 7). An ideal structure spectrum is shown in Figure 13. In addition, to achieve a good wet look, it is essential to have a minimum at Wc (Equation 1b). Finally, Lex (2004) claims that by exploiting certain ratios of elements, it is possible to achieve smoother appearance. If the shortwave values are 1 –

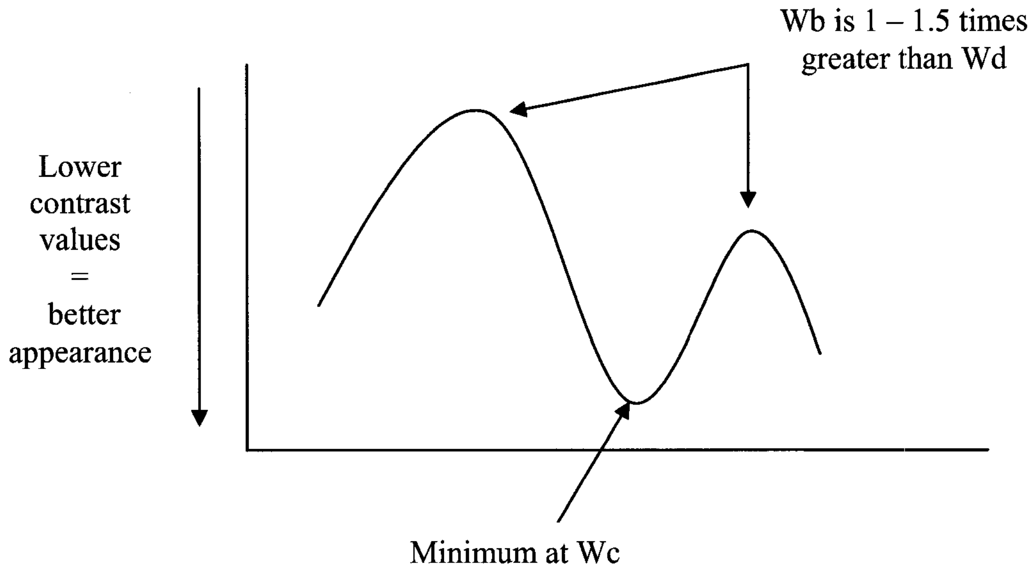


Figure 13 – Anatomy of an ideal structure spectrum

1.5 times greater than the longwave values, the shortwaves will mask the longwaves and the finish will appear smoother. In all cases, lower values on the structure spectrum produce a better appearance. Kigle-Böckler (2005) suggests that We is not a problem for low to middle class vehicles as it is masked by the shorter waves. We becomes a problem for luxury car manufacturers such as Rolls-Royce and Bentley whose vehicles are hand polished to remove these shorter waves. As a result, the longer We waves become noticeable.

2.6 Process Parameters

Lex (2004) has presented some theories for optimizing the paint process. His presentation incorporates the "tsunami" theory, also presented by Braslaw (2004). This theory, based on the physics of surface tension leveling, states that it is possible to level a wave with a wavelength that is at most 10 times the depth of the liquid under it (Braslaw, 2004). For example, 50 μm thickness of clear coat can level waves with a maximum wavelength of 500 μm of base coat. Therefore, according to this theory, du, Wa and small Wb elements can be leveled by clear coat. Lex (2004) also suggests reasons why an appearance element may be too high in a process. If the dullness values are too high, the clear coat material itself might be too milky. In addition, the very fine textures which contribute to dullness may be caused by dry spray which results when there is an excessive loss of solvent from the paint before it reaches its target and it cannot be leveled during cure. Dry spray might also cause the Wa values to be out of specification. Substrate influences are attributed to poor Wa, Wb, Wc and Wd values.

Lex (2004) states that vertical surfaces, which are impacted to a greater extent by gravitational forces, tend to have higher Wc and Wd values than horizontal surfaces. Lex (2004) also agrees that horizontally baked surfaces have lower longwave values (Wc and Wd) while shortwaves are thought to be uninfluenced by baking position.

A benchmark study conducted by BYK Gardner using European medium sized automobiles (Kigle-Böckler, 2004) found that a good quality appearance is indicated by contrast values below 30 for all appearance elements. Horizontal surfaces, such as hoods, which have better leveling capabilities, were found to have lower Wc and Wd values. Vehicles painted with silver, or other paints with high contents of metallic flake, had lower DOI values.

In contradiction to the "tsunami" theory, Wc and Wd values are increased by insufficient clear coat film thickness. Kigle-Böckler (2003) proposes that increasing clear coat film thickness improves flow and leveling characteristics and ultimately improves Wc and Wd values.

A second study investigating appearance was conducted by BYK Gardner (2002). This study involved identifying the influence of baking position, substrate roughness, film thickness and flattening agents on the appearance of a painted surface. In accordance with previous studies, it was found that horizontally baked surfaces exhibited better flow and leveling and consequently have lower longwave values than vertically baked surfaces. Shortwaves were not influenced by the baking position. Glass panels were found to afford the best appearance, while car body panels were found to result in high shortwave values. Wa, Wc and Wd values decreased with increasing film thickness. Finally, the addition of flattening agents was mainly found to influence fine structures resulting in better DOI values (BYK Gardner, 2002).

It becomes increasingly apparent that the flow and leveling behaviour of the paint has an important role in the final finish of a vehicle. Wilson (1997) modeled the drying process for a paint film. As a film of paint dries, any non-uniformities in the initial film thickness are removed under constant surface tension and eventually a film of relatively uniform thickness is produced. It was also found that waterborne base coats with a highly volatile co-solvent level faster than a waterborne base coat without a co-solvent, which level faster than a waterborne base coat with a low volatility co-solvent. Wilson (1997) further explains the drying model by stating that as the free surface begins to level, non-uniformities in the solvent concentration are created which cause surface tension gradients and enhance leveling. The free surface becomes flat, but the solvent concentration remains non-uniform and as a result, surface tension gradients continue to drive the flow. Surface tension forces then oppose the surface tension gradient forces and the process repeats itself. This infers that a long ambient flash time before a painted surface is heated and cured should result in better appearance. In contradiction to this model, Kigle-Böckler (2005) suggests that base coats appear rougher (i.e. have higher contrast values) as flash times increase.

Pierce and Schloff (1994) characterize leveling using a leveling half-time, which in theory is directly proportional to the viscosity of the film and the fourth power of the wavelength of disturbance and inversely proportional to the surface tension of the film and the cube of the film thickness. If the leveling half-time is sufficiently short, the film becomes smooth before drying and/or curing which causes the viscosity to increase to the point where no more flow is possible. It should be noted that non-Newtonian viscosity and solvent evaporation effects are thought to account for some of the deviation between theory and experimental results.

Pierce and Schloff (1994) also propose that surface tension variations across the wet paint film are the driving force for many coatings defects. These variations are most often due to localized temperature or concentration variations that occur as the coating dries or is cured. Shear forces act on a coating when it is applied and this promotes a forced spreading of the coating over the surface. Gravity contributes to the shearing action whenever the film is applied vertically and can lead to sags in the coating. Shear stress produced by gravity is resisted by the viscous force which is directly proportional to the velocity gradient. As a result, the maximum sagging velocity is at the free film surface and is directly proportional to the film density and the square of the applied film thickness. Pierce and Schloff conclude that if the velocity is sufficiently low, the coating will stop flowing due to drying before sagging becomes noticeable.

Orange peel corresponds to wavelengths between 1 mm and 6 mm (W_c and W_d), is often caused by poor leveling (Pierce & Schloff, 1994). It is thought to be a result of high film viscosity which restricts the leveling of the film and of surface tension gradient-induced flows. The use of lower solids coatings, a lower molecular weight resin or lower pigment loading may reduce the appearance of orange peel if high viscosity is determined to be the cause.

2.7 Design of Experiments

An important part of any research is setting up the experiment schedule. A major limitation in research is that the number of experiments required increases exponentially with the number of variables being investigated. Including too many variables can be time and resource prohibitive whereas using too few variables results in the experiments not yielding any information. To combat this, several different experimental designs have been established over the years. Two different types of designs of experiments (DOE) were used in this research. In the preliminary analysis, DaimlerChrysler paint operations specialists used a Plackett and Burman DOE (Plackett and Burman, 1946), a special class of resolution III, two-level fractional factorial designs often used to study main effects and to screen for important variables. This type of DOE assumes that there are no interactions between variables and in this specific situation, allowed eleven variables to be investigated in twelve runs.

A fractional factorial DOE is also used in this research. This type of DOE helps to reduce the number of runs to a manageable number. The runs that are performed are a selected subset of the full factorial design. Specifically, a ¼ fraction factorial design was used in this investigation. The ¼ fraction factorial design contains one-quarter as many design points as the full factorial design. In addition, the response is only measured at two of the possible eight corner points of the factorial portion of the design. It is important to note that when all factor level combinations are not run, some of the effects are confounded. These effects cannot be estimated separately and are said to be aliased. This indicates that two or more factors have been changed at the same time. For this reason it is important to choose the subset properly to achieve meaningful results. Choosing the proper subset often requires specialized knowledge of the process under investigation. In this study, the results of the Plackett and Burman analysis will be used in the fractional factorial DOE.

CHAPTER 3 – ANALYSIS OF PREVIOUS WORK

3.1 Directional Colour Design of Experiment Panels

To begin the study it was necessary to reduce the variables in the topcoat painting process to a manageable number. This was achieved by analyzing the results of a preliminary study involving several sets of panels known as "directional colour DOE panels" sprayed by PPG, a supplier of automotive paints to DaimlerChrysler. For the directional colour DOE panels, a Plackett and Burman design of experiments is used to evaluate new model year colours for their robustness and to exclude difficult-to-process colours early in the development phase. This experiment does not attempt to understand the effects of any single factor or combination of factors on the outcome of the appearance or to optimize any process settings. This DOE consists of twelve panels and investigates the effects of eleven variables at two levels. The variables tested in the directional colour DOE are summarized in Table 2. The values in the table are generic for the DaimlerChrysler materials and process. The paint fluidity is adjusted by determining the proper viscosity for the paint suggested by the manufacturer and adding an appropriate amount of reducing agent (water for waterborne materials and solvent for solventborne materials) to obtain the proper viscosity using the Ford #4 cup. After the process has been setup to accommodate the proper flash times and the nominal film thickness, the equipment settings are noted and manipulated to achieve the high and low settings required. Using the settings which result in nominal film thickness, the dehydration oven temperature can be selected to achieve the required dehydration solids percentage. This temperature is then adjusted to achieve the high and low levels of dehydration solids indicated by the DOE. Variables describing "air" refer to air pressures. Dehydration solids indicates the percent of solid content remaining in the paint film after it has passed through the post-base coat dehydration oven.

One of the twelve panels is a *target conditions* panel which is painted with ideal or nominal settings. The other eleven panels are painted with combinations of the variables at a high level or a low level. The high and low levels of process parameters are values

Table 2 – Plackett and Burman DOE variable summary for DuPont waterborne base coats

Variable	High Level	Low Level
Paint Age	Fresh	Aged
Paint Fluidity	+3 seconds viscosity	-3 seconds viscosity
Dehydration Solids	90%	80%
Booth Humidity/Temperature	58%RH/25.6°C	68%RH/20°C
Reciprocator Atomizing Air	+15%	-15%
Reciprocator Flow Rate	+20%	-20%
Clear coat Thickness	+10.2 μm	-10.2 μm
Bell Shaping Air	+15%	-15%
Bell Speed	+15%	-15%
Reciprocator Fan Air	+15%	-15%
Bell Flow Rate	+10%	-10%

which could reasonably occur at an assembly plant. In contrast to the assembly plant conditions, experimental facilities such as the ACRF are able to control both relative humidity and temperature. A Plackett and Burman directional colour DOE for DuPont waterborne base coats is provided in Table 3. The dehydration oven temperature is specific to the process set up at the ACRF, where a dehydration oven temperature of 85°C results in 85% dehydration solids, 82.2°C results in 80% dehydration solids and 87.8°C results in 90% dehydration solids.

Horizontally and vertically baked panels, treated as indicated in Table 3, were obtained for five colours: BB8, BPK, DA4, DBM and CB6. Each of the one hundred and twenty panels was measured with the wave-scan DOI five times and the contrast values for each structure size were averaged for that panel to reduce the influence of outliers. The data collected from the wave-scan DOI was analyzed using several statistical tests.

3.1.1 t-Test

The first statistical test used was a t-test. In preparation, the data was divided into several sub-tables, each containing the average appearance element values for a specific level of process variable. For example, one table would contain all the results for panels which were coated with fresh paint, while another table would summarize the information for

Table 3 – Plackett and Burman DOE for DuPont waterborne base coats

Run	Paint Fluidity	Dehyd. Oven Temperature	Booth humidity/ temperature	Bell Speed	Bell Shaping Air	Paint Flow Rate - Bells	Recip. Atomizing Air	Recip. Fan Air	Paint Flow Rate – Recip.	Clear coat Thickness (µm)	Paint Age
Target		85°C	63%Rh/25.6°C							50.8 H/45.7 V	Fresh
1	+3	82.2°C	68%Rh/20°C	-15%	-15%	-10%	15%	15%	20%	-10.2	Fresh
2	+3	87.8°C	58%Rh/25.6°C	15%	-15%	-10%	-15%	15%	20%	10.2	Aged
3	-3	87.8°C	68%Rh/20°C	-15%	15%	-10%	-15%	-15%	20%	10.2	Fresh
4	+3	82.2°C	68%Rh/20°C	15%	-15%	10%	-15%	-15%	-20%	10.2	Fresh
5	+3	87.8°C	58%Rh/25.6°C	15%	15%	-10%	15%	-15%	-20%	-10.2	Fresh
6	+3	87.8°C	68%Rh/20°C	-15%	15%	10%	-15%	15%	-20%	-10.2	Aged
7	-3	87.8°C	68%Rh/20°C	15%	-15%	10%	15%	-15%	20%	-10.2	Aged
8	-3	82.2°C	68%Rh/20°C	15%	15%	-10%	15%	15%	-20%	10.2	Aged
9	-3	82.2°C	58%Rh/25.6°C	15%	15%	10%	-15%	15%	20%	-10.2	Fresh
10	+3	82.2°C	58%Rh/25.6°C	-15%	15%	10%	15%	-15%	20%	10.2	Aged
11	-3	87.8°C	58%Rh/25.6°C	-15%	-15%	10%	15%	15%	-20%	10.2	Fresh
12	-3	82.2°C	58%Rh/25.6°C	-15%	-15%	-10%	-15%	-15%	-20%	-10.2	Aged

panels coated with aged paint. Table 4 illustrates the separation of data into sub-tables for t-test analysis

In the same way, twenty other sub-tables were created for the remaining ten variables. An F-test for variance was performed comparing the results from each pair of tables corresponding to high and low levels for a specific variable and each appearance element. Appearance elements whose F-tests showed no difference in variance were then subject to a two sample t-test assuming equal variances. Conversely, appearance elements whose F-tests showed differences in variance were subject to a two sample t-test assuming unequal variances.

Table 4 – Separation of data into sub-tables for t-test

Paint Age	Level 1	Fresh				
	du	Wa	Wb	Wc	Wd	We
Target	22.70	15.48	39.14	17.84	15.66	11.00
Panel 1	19.80	15.02	18.94	8.96	14.24	9.72
Panel 2	23.50	21.92	49.94	21.38	17.52	15.40
Panel 4	19.40	5.64	19.32	9.56	9.98	8.76
Panel 5	22.02	13.18	30.00	9.44	12.54	7.88
Panel 6	22.22	14.04	21.66	10.08	13.72	8.96
Panel 10	22.54	18.02	48.04	27.22	19.20	16.06

Paint Age	Level 2	Aged				
	du	Wa	Wb	Wc	Wd	We
Panel 3	15.90	8.22	21.04	11.54	10.38	10.54
Panel 7	20.50	12.92	21.98	9.14	12.82	8.72
Panel 8	23.62	9.94	33.54	12.72	10.72	10.62
Panel 9	22.20	15.38	30.70	12.16	13.98	10.14
Panel 11	24.48	22.50	51.76	22.20	17.10	15.56
Panel 12	22.60	17.28	38.42	12.96	12.94	9.90

Table 5 provides an example of an F-test and a t-test which were used to determine the impact of paint age on the Wb element for horizontal DBM panels. These tests were carried out for each of the 10 sets of panels – horizontally and vertically baked BB8, BPK, CB6, DBM and DA4 panels. In this example, F is less than F critical which indicates that the variances are not statistically different. Similarly, since the calculated t is less than t critical, the difference in the means is not significant. Therefore, paint age does not affect Wb. Note that two tailed critical values were used because a relationship was not known to exist between the variable and the appearance element.

Table 5 – An example of an F-test and a t-test to determine impact of paint age on Wb with horizontal DBM panels

F-Test Two-Sample for Variances

	Fresh	*Aged*
Mean	32.43428585	32.90666676
Variance	178.5076965	130.2650663
Observations	7	6
df	6	5
F	1.370342038	
P(F<=f) one-tail	0.373419034	
F Critical one-tail	4.950294397	

t-Test: Two-Sample Assuming Equal Variances

	Fresh	*Aged*
Mean	32.43428585	32.90666676
Variance	178.5076965	130.2650663
Observations	7	6
Pooled Variance	156.5792282	
Hypothesized Mean Difference	0	
df	11	
t Stat	[redacted]	
P(T<=t) one-tail	0.473559599	
t Critical one-tail	1.795883691	
P(T<=t) two-tail	0.947119198	
t Critical two-tail	2.200986273	

3.1.2 Regression Analysis

Regression analysis was the second statistical test to be used in the preliminary study. For this test, each of the process variables was coded for the high and low levels with a +1 and -1, respectively. This allowed all of the variables to be weighted evenly. A table was set up with the average appearance element values and all of the coded process

Table 6 – Process variables coded for high and low levels

All Data

	Paint Age	Paint Fluidity	Dehydration Solids	Booth humidity/ Booth temperature	Recip. Atomizing Air	Recip. Flow Rate	Clear coat Thickness	Bell Shaping Air	Bell Speed	Recip. Fan Air	Bell Flow Rate
Target	1	0	0	0	0	0	0	0	0	0	0
Panel 1	1	-1	1	-1	-1	-1	1	1	1	-1	1
Panel 2	1	1	-1	1	-1	-1	-1	1	1	1	-1
Panel 3	-1	1	1	-1	1	-1	-1	-1	1	1	1
Panel 4	1	-1	1	1	-1	1	-1	-1	-1	1	1
Panel 5	1	1	-1	1	1	-1	1	-1	-1	-1	1
Panel 6	1	1	1	-1	1	1	-1	1	-1	-1	-1
Panel 7	-1	1	1	1	-1	1	1	-1	1	-1	-1
Panel 8	-1	-1	1	1	1	-1	1	1	-1	1	-1
Panel 9	-1	-1	-1	1	1	1	-1	1	1	-1	1
Panel 10	1	-1	-1	-1	1	1	1	-1	1	1	-1
Panel 11	-1	1	-1	-1	-1	1	1	1	-1	1	1
Panel 12	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1

variables. A subset of this table is provided in Table 6. Each appearance element was regressed against the coded values for the process parameters.

Ten subsequent tables were established with one less process variable than the original table. For example, one table was set up with all the average appearance element values and all of the coded process variables except for paint age. The next table would be the same as the previous except that paint fluidity would be omitted and paint age would again be included. A regression analysis was performed with each of the average appearance element values as the dependant variable and the coded variables as the independent. This was done for each of the eleven tables (table one contains all the data and the ten subsequent tables contain all the data less one variable). The R-squared values of each regression are summarized. Table 7 summarizes the R-squared values resulting from the regressions for each appearance element for the horizontal DBM panels.

Table 7 – R-squared values for horizontal DBM panels

R-Squared

Variable Removed	du	Wa	Wb	Wc	Wd	We
None	0.976	0.988	0.904	0.997	0.995	0.996
Paint Age	0.974	0.956	0.889	0.994	0.99	0.841
Paint Fluidity	0.96	0.982	0.903	0.983	0.995	0.922
Dehydration Solids	0.787	0.819	0.183	0.606	0.692	0.612
Booth Humidity/Temperature	0.938	0.97	0.9	0.847	0.732	0.987
Reciprocator Atomizing Air	0.974	0.973	0.884	0.995	0.96	0.983
Reciprocator Flow Rate	0.969	0.98	0.899	0.976	0.995	0.994
Clear coat Thickness	0.976	0.94	0.882	0.991	0.96	0.88
Bell Shaping Air	0.895	0.98	0.904	0.996	0.989	0.925
Bell Speed	0.754	0.983	0.899	0.842	0.87	0.895
Reciprocator Fan Air	0.795	0.201	0.765	0.846	0.993	0.905
Bell Flow Rate	0.794	0.957	0.861	0.925	0.724	0.995

The R-squared values tabulated in Table 7 indicate the strength of the correlation between an appearance element and a process variable. For example, 97.6% of the variation in du can be explained when all of the variables are included in the regression. However, only 78.7% of the variation in du can be explained when dehydration solids is not included in the regression, indicating that approximately 18.9% of the variation in du is caused by dehydration solids. Note that reducing the amount of variables may cause the R-squared value to decrease since there are fewer variables to model the response. However, this test was used to screen the process for influential process parameters rather than the absolute influence of each variable.

3.1.3 Other Analysis

Correlation analysis using Minitab software (Minitab Inc., State College, USA), was also considered to analyze the DOE data. However, it was determined that significance plots could not be generated since there were zero degrees of freedom (no replicates).

3.1.4 Preliminary Results

Once all of the F-tests, t-tests and regressions had been completed, the results were compiled into tables. For each colour and baking orientation, a table was created which contained a list of all the process parameters and indicated whether any of the t-tests for the appearance elements was significant. An example of this summary table is shown In Table 8. All t-test summary tables can be found in Appendix A. This table (Appendix A) indicates that increasing the dehydration solids from the low level to the high level resulted in a significant change in the Wa, Wb, Wc and Wd values. It also indicates that changing the reciprocator fan air from the low level to the high level resulted in a significant change in the We value.

Table 8 - t-Test summary for DA4 horizontal panels

Summary	t-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Wa, Wb, Wc, Wd
Booth Humidity/Temp	
Reciprocator Atomizing Air	
Reciprocator Flow Rate	
Clear coat Thickness	
Bell Shaping Air	
Bell Speed	
Reciprocator Fan Air	We
Bell Flow Rate	

A second results table was created to summarize the results of the regression analysis. An example of a regression summary table is provided in Table 9. Additional regression summary tables can be found in Appendix A. As stated earlier, the initial regression was performed with all eleven variables in the DOE. Each subsequent regression contained one less variable. The values in the regression summary table (Appendix A) represent the influence of a particular process parameter on each appearance element. The R-squared value from each regression containing ten variables was subtracted from the corresponding R-squared value in the initial regression which had eleven variables. This value was converted to a percentage. A 25% cutoff value was selected and those parameters which account for greater than 25% of the variation in the regression (after controlling all other variables) are highlighted red. Yellow highlighted squares indicate those process parameters which account for between 20 and 24.9% of the variation in a regression. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame. Additional regression analysis was performed to ensure that there was a strong relationship (>0.64) between the appearance elements and the process parameters to be further investigated. The results of this analysis are included in Appendix A.

Table 9 - Regression summary table for DA4 horizontal panels

Influence of Variable	du	Wa	Wb	Wc	Wd	We
Paint Age	1.0	0.5	0.1	2.6	12.5	0.4
Paint Fluidity	0.0	5.0	0.7	0.1	1.8	0.7
Dehydration Solids	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Booth Humidity/Temperature	3.5	5.8	0.5	4.9	5.9	5.8
Reciprocator Atomizing Air	0.1	6.1	0.6	0.1	0.5	0.7
Reciprocator Flow Rate	3.7	0.7	0.2	4.7	8.5	2.2
Clear coat Thickness	6.9	2.4	2.6	2.8	5.7	2.1
Bell Shaping Air	[redacted]	18.1	4.9	1.9	10.1	7.7
Bell Speed	9.4	3.3	0.0	4.7	13.5	8.3
Reciprocator Fan Air	0.3	0.0	20.7	[redacted]	3.3	[redacted]
Bell Flow Rate	12.4	4.3	6.5	5.6	4.2	3.2

To check for correlation between the tests, a third table was created. This table documents each time a statistical test resulted in a significant impact on appearance. An example of this table is provided in Table 10. In this table, a T represents t-tests (n=11) where the parameter was significant at the 95% level and an R represents regressions that resulted in a difference of $R^2 > 25\%$ for a particular process parameter and appearance element combination. Since there is no critical value for the change in R^2, some cells contain R only.

Finally, four additional summary tables were compiled – a t-test summary table (Table 11), a regression summary table (Table 12) and two overall summary tables (Tables 13 and 14) for a combination of all ten of the panel sets. The t-test summary table (Table

Table 10 - t-Test and regression summary table for DA4 horizontal panels

Variable	du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	R	T,R	T,R	T,R	T,R	R
Booth Humidity/Temperature						
Reciprocator Atomizing Air						
Reciprocator Flow Rate						
Clear coat Thickness						
Bell Shaping Air	R					
Bell Speed						
Reciprocator Fan Air				R		T,R
Bell Flow Rate						

11), summarizes the number of times a particular process parameter was significant for an appearance element for any of the sets of panels using a t-test. In the same manner, a regression summary table (Table 12) was created which shows the number of times a particular process parameter was significant for an appearance element for any of the panel sets using regression analysis. In both cases, the tally column/row sums the total number of times a process parameter or appearance element was significant. Note that the sample size for the t-test was 5 and there were two levels of independent variables. Also note that there were two levels of independent variables for the regression analysis and the sample size was 12.

Table 11 - Overall t-test summary table

T-test

Variable	Du	Wa	Wb	Wc	Wd	We	[redacted]
Paint Age	1	1	1	1		1	
Paint Fluidity						1	
Dehydration Solids	4	3	3	4	3	3	
Booth Humidity/Temperature				1		1	
Recip Atomizing Air			1				
Recip Flow Rate					2	1	
Clearcoat Thickness		1		2	3	2	
Bell Shaping Air						1	
Bell Speed						1	
Recip Fan Air	3	2			1	1	
Bell Flow Rate		1		1		1	
[redacted]							

Table 12 – Overall regression summary table

Regression

Variable	Du	Wa	Wb	Wc	Wd	We	[redacted]
Paint Age	1	1	1	1	1	1	
Paint Fluidity						1	
Dehydration Solids	3	2	5	3	4	2	
Booth Humidity/Temperature				1	1	1	
Recip Atomizing Air			1				
Recip Flow Rate					2	1	
Clearcoat Thickness	1	2		2	2		
Bell Shaping Air	1			1		1	
Bell Speed				1	1		
Recip Fan Air	3	3		1	1	1	
Bell Flow Rate	1	1		1	1		
[redacted]							

The final two tables were created by summing the tally columns and rows in the T-test and regression summary tables. Table 13 summarizes the impact of any process parameter on appearance elements. This number indicates the frequency with which a particular appearance element is affected by any process parameters and is the sum of the tally rows in Figures 11 and 12. This table suggests that Wb (highlighted in yellow), which is affected by any of the process parameters a total of only thirteen times, may be influenced more by substrate variables such as surface roughness or coating properties than variables in the coating process. Table 14 summarizes the impact of each process parameter on appearance and is the sum of the tally columns in Figures 11 and 12. The green highlighted squares are the process parameters which are most likely to affect the appearance of a painted surface and will be used in upcoming DOE matrices.

Table 13 – Summary of impact of process parameter on appearance elements

Element Total	
18	Du
17	Wa
13	Wb
20	Wc
22	Wd
20	We

Table 14 – Impact of each process parameter on appearance

	Variable Total
Paint Age	[illegible]
Paint Fluidity	2
Dehydration Solids	[illegible]
Booth Humidity/Temperature	5
Recip Atomizing Air	2
Recip Flow Rate	[illegible]
Clearcoat Thickness	[illegible]
Bell Shaping Air	4
Bell Speed	3
Recip Fan Air	[illegible]
Bell Flow Rate	[illegible]

From this preliminary study, some important conclusions can be drawn. Variables having an effect on appearance six times or more were: paint age, dehydration solids, clear coat thickness, reciprocator flow rate, reciprocator fan air and bell flow rate have the most influence on the appearance of a painted surface. It was also found that Wb was least likely to be impacted by any process variable.

3.2 Clear Coat Film Thickness Study

An independent investigation of the effect of clear coat thickness on appearance elements was conducted by ACRF process engineers in June 2004. Coil coated aluminum panels (for further explanation, see Section 4.2) were sprayed with DCT 5555 clear coat at varying line speeds and with two different ambient flash times – 2 minutes and 12 minutes. Other than these two variables, the clear coat panels were painted under identical conditions. Conveyor speeds were varied between 2.12 m/min (7 fpm) and 6.13 m/min (20 fpm) to achieve different film thicknesses. The slower the conveyor speed the more accumulation and the thicker the clear coat on the panel. Both horizontal and vertical panels were sprayed. The panel rack was set up with three horizontal and three vertical panels as shown in Appendix B. The coating equipment was set up to deliver 50.8 μm (2.0 mils) film thickness at 2.76 m/min (9 fpm). Note that film thickness refers to dry (after curing) film thickness. In total, 20 sets of panels were sprayed at conveyor speeds ranging between 2.12 and 6.13 m/min (7 and 20 fpm). All panels were cured in the same orientation using panel racks and a laboratory batch oven. The environmental set points and equipment specifications are included in Appendix B.

All panels were measured with the wave-scan DOI and the data was compiled into a summary spreadsheet. The 2 minute flash and the 12 minute flash film thickness and appearance element data were tested for statistical differences using a paired t-test. It was determined that the 2 minute and 12 minute flash time data must be analyzed separately since statistical differences in Wa and Wb were found. Next, the paired t-test was used to determine if there were statistical differences in appearance elements and film thickness between horizontal and vertical panels for each of the flash time datasets. In both cases, it was found that the horizontal and vertical film thicknesses were statistically different for corresponding line speeds and flash times. The result of the paired t-test between horizontal and vertical panels which had a 12 minute ambient flash time is shown in Table 15.

A plot of appearance element versus film thickness was created, with each plot having four data series – horizontal panels with 2 minute flash, vertical panels with 2 minute flash, horizontal panels with 12 minute flash and vertical panels with 12 minute flash. In each case, third order polynomial trend lines were used to fit the data. As an example, a plot showing Wd values versus film thickness for each of the four sets of panels is shown in Figure 14. The remaining plots are included in Appendix C. The data indicated by

Table 15 – Determination of difference between horizontal and vertical clear coat panels: film thickness

t-Test: Paired Two Sample for Means – Film Thickness

	Horizontal Panels	*Vertical Panels*
Mean	1.535543478	1.42442029
Variance	0.253847008	0.183127616
Observations	23	23
Pearson Correlation	0.977242913	
Hypothesized Mean Difference	0	
df	22	
t Stat	[redacted]	
P(T<=t) one-tail	0.000155835	
t Critical one-tail	1.717144187	
P(T<=t) two-tail	0.000311669	
t Critical two-tail	2.073875294	

blue diamonds in Figure 14 represents Wd values for each of the panels sprayed horizontally and baked after a two minute ambient flash. The pink squares represent Wd values for panels sprayed vertically and baked after a two minute ambient flash. The orange triangles represent Wd values of panels sprayed horizontally and baked after a twelve minute ambient flash. Finally, the light blue crosses represent Wd values for

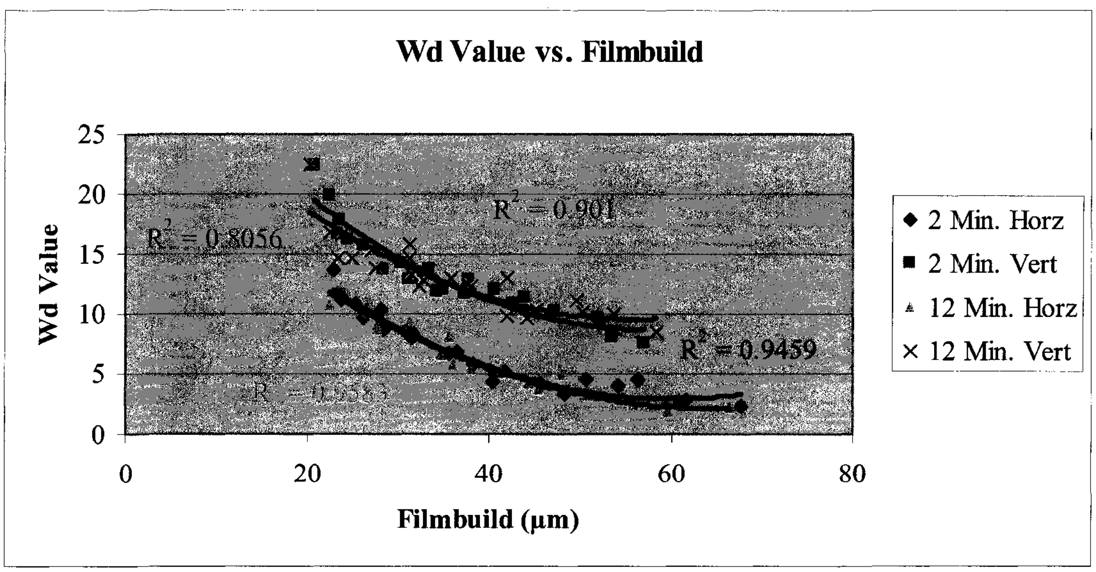


Figure 14 – Plot of Wd vs. clear coat film thickness

panels sprayed vertically and baked after a twelve minute ambient flash. For each data series, the R-squared value was calculated and is indicated in the corresponding colour on the graph. The R-squared values for all du and We relationships and vertical Wb relationships were less than 0.64, the criteria used to determine whether there was a strong relationship (Devore, 1982). However, strong relationships between Wa, Wb, Wc and Wd and film thickness were found (Appendix C). Groups of four and five data points were used for each of the appearance elements affected by clear coat film thickness in a t-test to determine the point at which applying additional clear coat ceases to improve the appearance of the surface. A summary of the breakpoints is provided in Table 16, where 2 and 12 refer to the amount of ambient flash time, in minutes. H and V represent horizontal and vertical, respectively, the orientation of the panel during the painting process. It is noted that for vertically sprayed panels, the Wa values increase as clear coat thickness increases after the breakpoint.

Table 16 – Breakpoint summary for clear coat film thickness (μm)

	Wa	Wb	Wc	Wd
2H	>67.8	36.6	38.4	>67.8
2V	26.2*	--	34.3	>57.2
12H	>66.5	34.8	38.1	>66.5
12V	41.9*	--	38.1	>58.4

* contrast value increases after breakpoint

3.3 Summary of Preliminary Experiment

In the first two phases of the study, statistical analysis was used to identify process parameters having significant impacts on appearance. The ACRF archives then scanned to find completed studies which investigated the impact of process parameters on appearance. The data from these studies was further analyzed. From the first phase (Appendix A), it was determined that paint age, clear coat film thickness, dehydration solids, reciprocator flow rate, bell flow rate and reciprocator fan air have the most impact on a vehicle's appearance. Dehydration solids were responsible for this impact nearly fifty percent of the time. All variables having an effect on appearance more than five times were considered important. Paint age was removed from consideration due to the difficulties it would present in the experimentation phase. Booth humidity/temperature was investigated in its place. Wb was determined to be the least likely to be impacted by any process variable.

In the second phase, a study investigating the effects of clear coat thickness on appearance which had been previously conducted at the ACRF was found. The results from this study (Appendix C) were analyzed and it was found that the Wa, Wb, Wc and Wd portions of the structure spectrum are significantly affected by clear coat film thickness. Both horizontal and vertical panels were analyzed. It was determined that for vertical panels, a film thickness of approximately 35 μm (1.35 mils) results in optimal Wa, Wb and Wc measurements. Increasing the clear coat film thickness past this point will not improve the appearance and can result in worse Wa and Wb values. It was also determined that for horizontal panels, a film thickness of approximately 38 μm (1.5 mils) results in optimal Wb and Wc measurements. Increasing the film thickness to 67.8 μm (2.7 mils) for horizontal surfaces results in improvement in Wa and Wd. Further improvement may be possible with thicker films, which were not tested. Increasing the film thickness to 57.2 μm (2.25 mils) for vertical surfaces always results in an improvement in Wd. Again, the optimal film thickness may not have been reached. In all cases, increasing the clear coat film thickness results in an improvement in Wd values. It should be noted that testing was ceased after 67.8 μm (2.7 mils) of clear coat was applied (i.e. 2.12 m/min or 7 fpm) since the clear coat began to sag on the vertical panels.

It was decided that there had been enough experimentation involving the impact of clear coat film thickness on appearance and this variable was removed from further studies. As a result, booth humidity/temperature, dehydration solids, bell flow rate and reciprocator flow rate and fan air were further investigated.

CHAPTER 4 – MATERIALS AND METHODS

4.1 Testing Facility

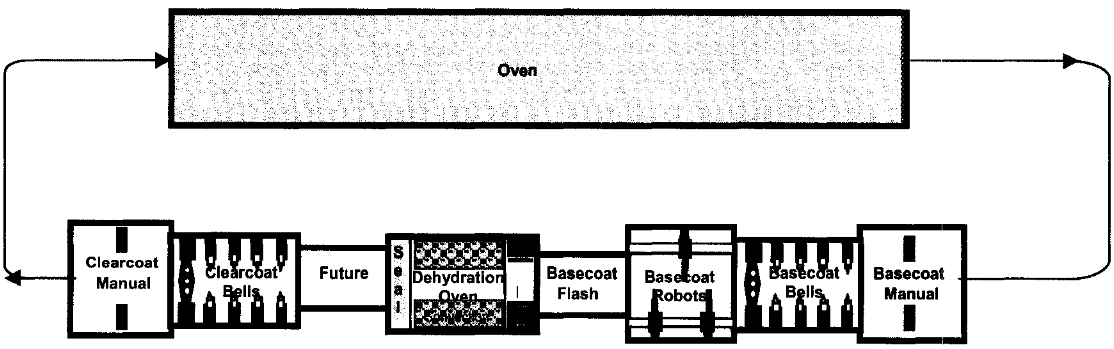


Figure 15 – ACRF topcoat and oven cure process flow diagram

The Automotive Coatings Research Facility (ACRF) is a state of the art topcoat simulator located within the University of Windsor/DaimlerChrysler Automotive Research and Development Centre (ARDC) in Windsor. The facility features a reversible, multi-speed conveyor that gives the engineers the flexibility to create appropriate flash times between the application of successive layers of paint. The facility also includes manual preparation zones where panels can be prepared for coating, bell zones where rotary bell atomizers apply paint electrostatically and robot zones where air atomizing spray guns attached to robot arms apply paint non-electrostatically. The base coat bell zone consists of eleven bells – three overhead bells located on one bell machine which spray the horizontal surfaces of a vehicle and eight bells on individual bell machines which spray the vertical surfaces of the vehicle. Refer to Figure 15 for the layout of the bells. Aerobell Copes bells, manufactured by ITW Ransburg (Angola, USA), are configured as indirect (external) charging electrostatic applicators for use with paints with high conductivities in the base coat bell zone. High voltage is applied to the six-probe charge ring located on the exterior of the bell assembly. A picture of an indirect charge configured bell is given in Figure 16 (left). The paint is atomized by spinning the grounded bell cup at a high speed (tens of thousands of rotations per minute) and the electrostatic charge is applied to the atomized paint particles during transfer to the vehicle via the electrostatic field generated by the charge ring.

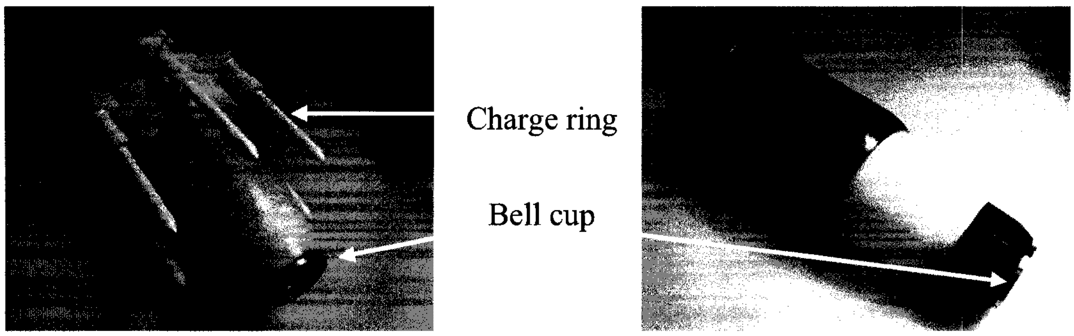


Figure 16 - Aerobell Copes indirect charge bell (left) and Aerobell Copes direct charge bell (right)

A similar setup is used in the clear coat bell zone where three overhead bells attached to a single bell machine spray horizontal surfaces and eight bells on separate bell machines spray vertical surfaces. The Aerobell Copes bell is also used in the clear coat zone; however, it is configured for the direct charge of paints with low conductivities by removing the exterior charge ring and inserting the high voltage cable into the base of the bell. A picture of a direct charge configured bell is given in Figure 16 (right). The paint enters the bell cup through a charged fluid tube. The charged paint is then atomized by the bell cup and transferred to the vehicle. In both cases, an LRPM4001-01 70 mm serrated Aerobell titanium bell cup (ITW Ransberg Electrostatic Systems, Toledo, USA) was used.

The facility's base coat robot zone consists of three IRB 5403 robots (ABB Flexible Automation, Byrne, Norway). These robots have seven axes of freedom and are equipped with non-electrostatic spray gun attachments. This specific project utilized an EFC ESS19 spray gun (EFC Systems Inc., Havre de Grace, USA) with an A70B cap which contains a 1.0 mm restrictor that regulates the fluid flow rate and a 106A50 nozzle which regulates the air flow that controls the fan pattern and the atomization of the paint. A picture of the non-electrostatic spray gun is given in Figure 17.

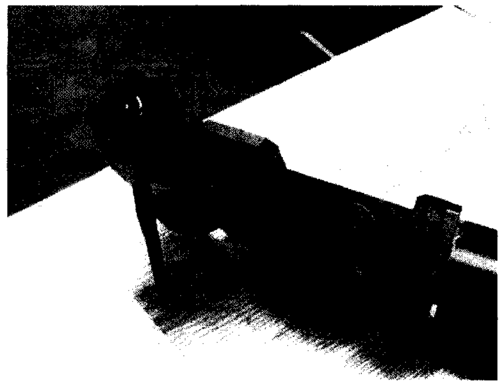


Figure 17 – Non-electrostatic spray gun attachment for use on IRB 5403 robots

The heated flash area separates the base coat and clear coat spray booths. It consists of an infrared (IR) zone, a convection zone and a recirculating heater box. The IR zone is not generally used and acts as an extension to the basecoat vestibule. In the convection zone, excess water is dehydrated from the paint before the clear coat is applied. This zone receives air at a rate of 850 m^3/min (30,000 ft^3/min) from the heater box (Haden, 1999). The air supply system is controlled by closed-loop Programmable Logic Control (PLC) Proportional Integral Derivative (PID) algorithms. The PID interface is applied to all process control operations that require continuous closed-loop control. In addition to this convection zone, the environmental conditions in each of the spray booths and the curing oven use PID interfaces.

4.2 General Experimental Procedure

Since substrate roughness is known to influence the appearance of a painted surface, it was important to select the smoothest, most uniform substrate available. Coil-coated aluminum, dipped electro-coated and spray-primed panels were considered. The coil-coated aluminum panels were obtained from ACT Laboratories. This type of panel begins as a 0.762 mm (0.03 inch) thick sheet of aluminum. It travels along a high speed conveyor line where it is coated with approximately 10.2 μm (0.4 mils) of a primer-like coating. The sheets are then cured at a high temperature and rolled into coils. When needed, they are cut to the required size. For this project, 30.5 cm x 45.7 cm (12 inch x 18 inch) coil-coated aluminum panels were used. The dipped electro-coated panels were also obtained from ACT Laboratories. Sheets of 0.787 mm (0.031 inch) thick steel are cut to 25.4 cm x 25.4 cm (10 inch x 10 inch) and pretreated to remove any residual oils and greases. The panels were then dipped into ED 6100H lead-free cathodic epoxy electro-coat mixture before they are cured in an oven. Finally, 10.2 cm x 30.5 cm (4 inch x 12 inch) steel panels were obtained from ACT Laboratories. These panels were affixed to the ACRF panel rack, wiped with presoaked rags containing 85% isopropyl alcohol and 15% de-ionized water (Contec, Spartanburg, USA) and with BS20CB tack rags (Contec, Toledo, USA). The panels were coated with approximately 55.9 μm (2.2 mils) of PPG DPX1809 liquid anti-chip primer which was applied and cured using ACRF equipment.

These three types of panels were then measured to determine which type of panel had the smoothest, most consistent surface. A Taylor/Hobson Surtronic 10 Ra profilometer and an Elcometer 355 were used in this investigation. A profilometer is an instrument which measures the surface roughness of the substrate. A stylus traverses a 5 mm portion of the substrate and outputs a numerical assessment of the roughness of a surface using the Ra method which averages the ten highest peaks on the surface. The Elcometer 355 is a dry film thickness gauge which uses magnetic induction to determine the thickness of the coating. Three magnetic coils are used – the centre coil is powered by the instrument and a coil on either side of the centre coil detects the magnetic field. When there is an absence of magnetic materials influencing the probe, the magnetic field affects the detecting coils equally. As the probe approaches a magnetic substrate, the field becomes unbalanced. A net voltage is produced between the detecting coils, which is related to the distance between the probe and the substrate, enabling the film thickness to be determined (elcometer, 2006). Depending on the size of the panel, the number and the location of the readings taken with each instrument varied. Plastic templates created specifically for each panel size were used to keep track of the reading locations. To study the consistency of the surface roughness on each substrate, several of each type of panel were measured using the Taylor/Hobson profilometer. Four columns of nine readings for a total of thirty-six readings were taken on three 30.5 cm x 45.7 cm (12 inch x 18 inch) coil-coated aluminum panels. Three columns of five readings were taken on four 25.4

cm x 25.4 cm (10 inch x 10 inch) dipped electro-coated panels. One column of six readings was taken on four 10.2 cm x 30.5 cm (4 inch x 12 inch) PPG DPX1809 spray primed panels. To analyze the film thickness consistency for each of the substrates, several of each type of panel were measured using the Elcometer 355. Eighteen columns of twelve readings for a total of two hundred and sixteen readings were taken on three 30.5 cm x 45.7 cm (12 inch x 18 inch) coil-coated aluminum panels. Three columns of three readings were taken on four 25.4 cm x 25.4 cm (10 inch x 10 inch) dipped electro-coated panels. One column of twelve readings was taken on four 10.2 cm x 30.5 cm (4 inch x 12 inch) ACRF DPX1809 spray primed panels. The layout of both the profilometer and the Elcometer readings is provided in Appendix D. The panel with the most consistent (lowest standard deviation) values was chosen as the substrate for the DOE. It was found that the dipped electro-coated panels had the most consistent surface and were therefore used as the substrate in all experiments. The profilometer and Elcometer readings are found in Appendix D.

All DaimlerChrysler assembly plants are guided by material standards and standard operating procedures. MS-PA-55-05.5D – Material Standard – 2006 Model Year is a standard that describes the physical constants for waterborne base coats. The colour specific paint application parameter specifications for DA4 silver steel base coat and RK – 8064 clear coat, the materials used in these experiments, are documented in this standard and are provided in Table 17. Since DuPont base coats are known to exhibit non-Newtonian behaviour (changing viscosity with changing shear stress), the Brookfield test (ASTM D2196-99), which is more representative of circulating plant conditions, was used to measure the viscosity of the base coat material while the viscosity of the clear coat, a fluid exhibiting Newtonian behaviour (constant viscosity with changing shear stress), was measured using the #4 Ford Cup test (ASTM D1200-94). The Brookfield instrument is used to measure shear rates ranging from 0.1 – 1.0 sec^{-1} and the Ford cup is used to measure shear rates less than 20 sec^{-1} (Vincent, 2004). Brookfield test results are measured in poise and #4 Ford Cup tests are measured in seconds.

Table 17 – Colour specific paint application parameters

Colour	Minimum Application Dry Film Thickness (μm)	Viscosity	Wt. Solids (%)
DA4	15.2 (0.6 mils)	0.2 ± 0.1 poise	22.5 ± 1.5
RK-8064	38.1 (1.5 mils)	47.5 ± 2.5 sec	55.5 ± 1.5

PSOP6001 – Main Colour – Waterborne is the document that describes a standard procedure for the application of waterborne basecoats and their corresponding clear coats in all assembly plants. This work instruction defines the activities, information, documentation, tools and resources required to ensure a quality finish at an assembly plant. Since this procedure is a requirement for all DaimlerChrysler facilities, in order to best simulate "real" conditions, the experimental process was set up to adhere as closely as possible to this standard. However, it is important to point out that performing these tests by painting vehicle bodies is cost prohibitive and 25.4 cm x 25.4 cm (10 inch x 10 inch) electro-coated steel panels affixed to a panel rack were used as a substitute for a vehicle body. The panel rack is 2.72 m x 0.88 m (106 inches x 34.5 inches) and is constructed of sheets of steel mesh. The entire rack is wrapped in heavy duty aluminum foil to facilitate clean up after the panels have been sprayed.

All process material specifications including paint temperature and viscosity, process booth specifications such as temperature and humidity as well as a process flow diagram are described in PSOP6001. The specifications for the materials used in this project, DuPont DA4 Silver Steel, a grey-blue waterborne metallic base coat and DuPont RK-8064 Generation IV ESW, a one component clear coat, are provided in Tables 18 and 19 below. A standard DaimlerChrysler process flow diagram is provided in Figure 18.

Table 18 – Material application temperature specifications (DuPont)

Coating	Composition	Paint Temperature
Waterborne base coat	Polyurethane/polyester dispersion	23.9 – 29.4 °C
Solventborne clear coat	Silane	32.2 °C

* ± 1.1 °C at set point

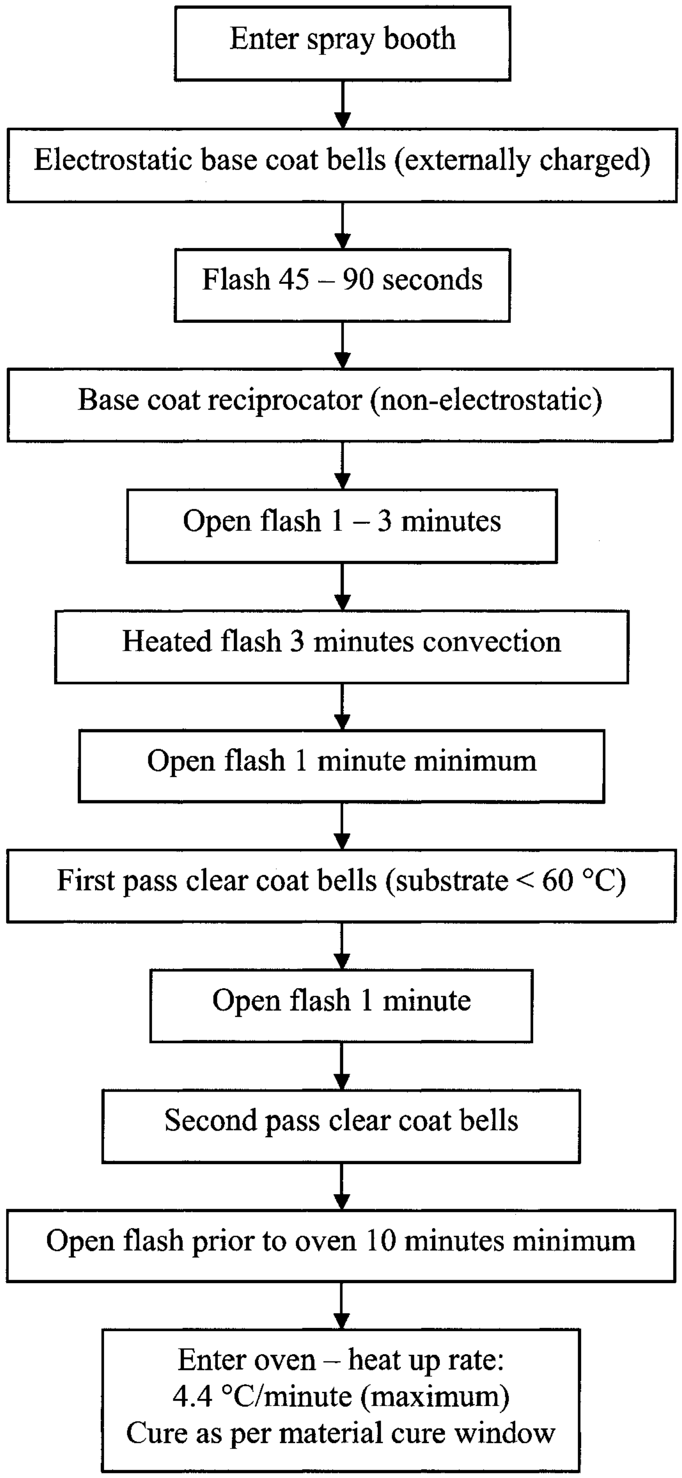


Figure 18 – DaimlerChrysler standard process flow

Table 19 – Process booth environmental specifications (DuPont)

Booth Parameter	Value
Basecoat zone temperature	26.7 ± 2.7 °C
Basecoat zone humidity	65 ± 5 % RH
Clear coat zone temperature	26.7 ± 2.7 °C
Clear coat zone humidity	≥ 50 % RH

A third document issued by the paint supplier identifies the cure window of the material. The specifications for silver steel and RK-8064 established by these three documents were used to set up the process at the ACRF. The material temperature is controlled in the facility's paint mix room and the process booth conditions are controlled using a PLC program in the control room. The standard process flow diagram was used to establish the settings for the application equipment. The flash times, specified in the instruction, set the targets for conveyor timing. Trial and error methods were used to select conveyor speeds through the different zones in the process to yield the proper flash times. The minimum dry film thickness (film build) specified by the material standard was also used as a target. Again, trial and error methods were used to establish values of flow rate, shaping air and bell speed in the bell zone and flow rate, fan air, atomizing air and tip speed in the robot zone that, in combination with the conveyor speed, yield a dry film thickness slightly above the minimum specified film thickness. Finally, Datapaq (Datapaq Inc., Wilmington, USA) software and instrumentation were used to create the nominal cure conditions as specified by the material's cure window. This instrument uses thermocouples to measure the metal temperature of a panel and the ambient temperature in the laboratory batch oven [NFPA 86 class "A" oven, model number 49D-650 (Precision Quincy, Woodstock, Il.)] as a function of time during the cure phase. The cure window for RK-8064, the clear coat used in this project, is attached in Appendix E. All panels were cured in the same orientation in the laboratory batch oven.

A fractional factorial DOE was created using Minitab software. From the preliminary tests, the number of variables in the topcoat process was reduced from eleven to seven. Clear coat film thickness had already been independently investigated (Section 3.3) and paint age was not considered due to the difficulties arising from aging paint, leaving five variables to be investigated. Selecting three replicates, two levels and a maximum of twenty-four sprayouts (experiments), a five factor, resolution III, ¼ fractional factorial DOE for dehydration solids, booth temperature and humidity, bell flow rate, reciprocator flow rate and reciprocator fan air was established. A quarter fractional factorial DOE can also be used to analyze for second order interactions. It was chosen for its ability to generate a large amount of data with the least amount of required resources. The following table summarizes the DOE. The complete DOE is provided in Appendix F.

Table 20 – Design of experiment summary

Variable	High Level	Low Level
Dehydration Oven Temperature	87.8 °C (190F)	82.2 °C (180F)
Booth Temperature/humidity	68%RH/20°C	58%RH/25.6°C
Bell Flow Rate	310/260 cm^3/min (+10%)	250/210 cm^3/min (-10%)
Reciprocator Flow Rate	420 cm^3/min (+20%)	280 cm^3/min (-20%)
Reciprocator Fan Air	360 L/min (+15%)	240 L/min (-15%)

The dehydration oven temperatures were selected such that 80% and 90% solids were achieved when a panel coated with the nominal film thickness was heated in the dehydration oven for three minutes at 82.2°C and 87.8°C, respectively. As indicated earlier, the bell flow rates were selected such that a specified film thickness was obtained when the panel passed through the base coat bell zone at a speed that created the proper flash time between the application of paint in the base coat bell and robot zones. In Table 20, two bell flow rates are specified for each level. Since different film thicknesses are required for horizontal and vertical surfaces and the conveyor speed must remain constant, it is necessary to adjust the bell flow rate to achieve the proper film thickness. The first flow rate (eg. 310 cm^3/min) is used to spray vertical surfaces and the second flow rate is used to spray horizontal surfaces (eg. 260 cm^3/min). At the ACRF, both temperature and relative humidity are controllable at the same time. These settings were chosen to repeat the same levels as the directional colour DOE reported in Section 3.1. The previous DOE did not consider any interactions between variables.

This DOE assigned A = dehydrations solids, B = booth humidity/temperature, C = reciprocator flow rate, D = reciprocator fan air and E = bell flow rate. In addition, a confidence level of 95% was selected for its design.

Prior to spraying the panels, samples of both the base coat and the clear coat were sent to the lab for viscosity, solids and density testing. The results of these tests are included as Appendix G. As noted earlier, the Newtonian RK-8064 clear coat was tested using a standard test closely related to ASTM D1200-94 which describes a test for viscosity using the Ford Viscosity Cup. In this test, the Ford Viscosity Cup C104 (Ford Viscosimeter, Lincoln Park, USA) is filled with the liquid to be measured. The time from when the material begins to flow through the standard orifice until the first break in the stream is called the efflux time and varies directly with the viscosity of the material. Conversely, the non-Newtonian DA4 base coat requires the use of a test which resembles ASTM D2196-99 which is the standard test method for rheological properties of non-Newtonian materials by rotational (Brookfield type) viscometer. Specifically, the Brookfield DV II+ viscometer (Brookfield Engineering, Brookfield, USA) is used in DaimlerChrysler materials engineering laboratories. This test determines the viscosity by measuring the torque on a spindle rotating at a constant speed in the material. In both cases, fluid temperatures, revolutions per minute and spindle types differing from those used in the standards are used for testing simplicity and also to satisfy DaimlerChrysler comparison criteria. The solids test is closely based on ASTM D2369-01, the standard test method for volatile content of coatings. This test determines the weight percent of volatile contents for solventborne and waterborne coatings by measuring the weight of material before and after it is heated to 110 ± 5°C for 60 minutes. Although the ASTM standard specifies that duplicate samples must be measured, DaimlerChrysler procedures only require one sample to be prepared. Finally, ASTM D1475-98, the standard test method for density of liquid coatings, inks and related products, is used to determine the density of the material. The density of distilled water at a specific temperature is used to calibrate the volume of a container. The weight of the same container filled with the material is determined and the density of that material is calculated with respect to the density of the distilled water.

To ensure consistency in the process, after every five runs, the bells and the gun tip were cleaned, samples of both the clear coat and the base coat were sent to the lab for viscosity, solids and density testing and a run with the target conditions was completed. A summary of the project parameters used in this experiment is supplied in Appendix H.

Each time a set of panels was sprayed the procedure outlined below was followed.

1. The environmental conditions for each booth (base coat manual, base coat bell, base coat robot, clear coat bell and clear coat manual), specified by the DOE (Appendix F), were entered into the PLC through the control room computer.
2. The dehydration oven temperature specified by the DOE (Appendix F) was entered into the PLC through the control room computer.
3. The conveyor speeds previously established to emulate the flash times specified by the DaimlerChrysler standard operating procedure were entered into the computer on the conveyor platform.
4. Four 10.2 cm x 7.6 cm (4 inch x 3 inch) aluminum foil rectangles, labeled A, B, C and D were weighed using the AA-250 balance (Denver Instrument Co., Denver, USA). The weight of each foil was noted as the W_{BS} (weight before spray).
5. The panel rack was set up according to the schematics below (Figures 19 and 20). For each experiment, six cold-rolled steel 10.2 cm x 30.5 cm (4 inch x 12 inch) panels and four PPG ED6100H 25.4 cm x 25.4 cm (10 inch x 10 inch) electro-coated panels were used. Two cold-rolled steel panels were used to support the foils used to establish the dehydration solids content. Foils A and B were placed on the vertical surface, while foils C and D were placed on the horizontal surface. These foils were held in place with thin magnetic frames. The remaining four cold-rolled steel panels were used as film build panels. Initially, two of these film build panels were placed on the panel rack – one on the vertical surface and one on the horizontal surface. The remaining two film build panels were labeled and used later in the process. The four electro-coated panels were used as appearance panels. On each surface, horizontal and vertical, one panel was labeled "clear coat only" and the other was labeled "total" (base coat and clear coat). All four of the electro-coated panels were wiped with rags

presoaked with 85% isopropyl alcohol and 15% de-ionized water (Contec, Spartanburg, USA) and BS20CB tack rags (Contec, Toledo, USA). The "clear coat only" panels were covered with aluminum foil affixed with high temperature masking tape.

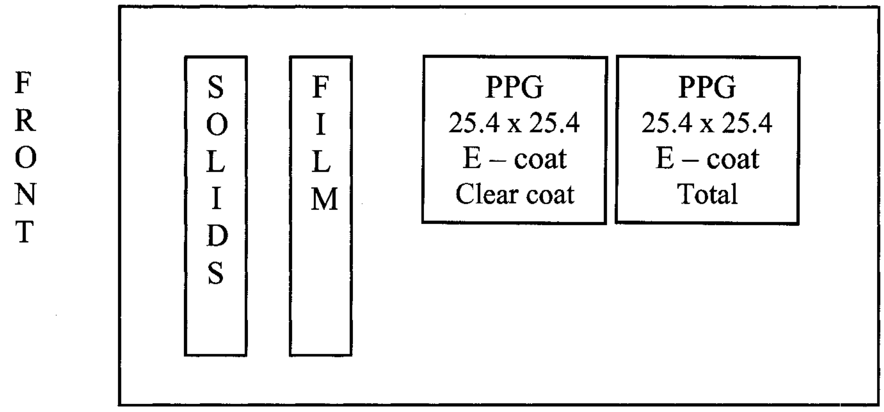


Figure 19 – Horizontal panel placement - Panels were placed on the centre row of the panel rack as follows beginning from the front: solids panel – bolt 1, film build panel – bolt 2, clear coat only panel – bolt 4, base coat + clear coat panel – bolt 6

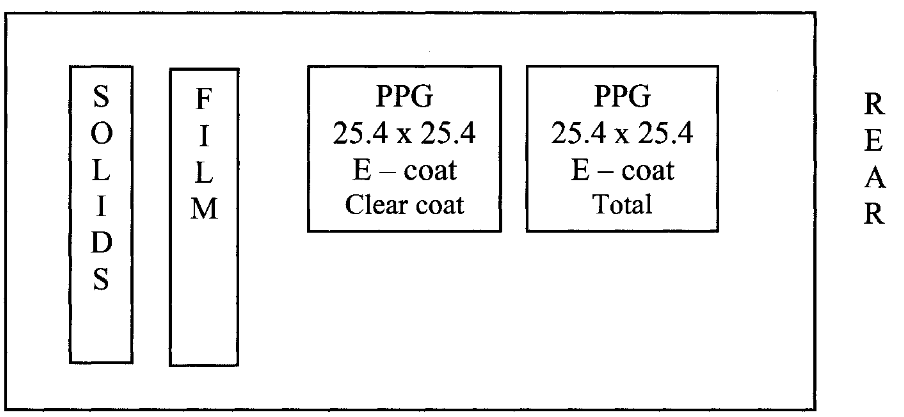


Figure 20 – Vertical panel placement – Panels were placed on the top row of the panel rack as follows beginning from the rear: base coat + clear coat panel – bolt 3, clear coat only panel – bolt 5, film build panel – bolt 7, solids panel – bolt 8

6. The bell flow rate and reciprocator fan air and flow rates were entered at the control console. Prior to spraying the panels, the equipment was tested to ensure the settings could be achieved.

7. The panel rack was sprayed with the base coat bells and the base coat robots.
8. In the base coat vestibule (Base coat flash in Figure 15), the A and C foils were removed, weighed and placed in the oven. The weights of these solids were noted as W_S (weight after spray).
9. The panel rack passed through the dehydration oven. When the DOE called for 90% solids, in addition to increasing the temperature, the panel rack was stopped in the dehydration oven for 2.5 minutes for a total dehydration time of 5.5 minutes.
10. In the clear coat vestibule (Future in Figure 15), the B and D foils were removed, weighed and placed in the oven. The weights of these solids were recorded as W_D (weight after dehydration).
11. The panel rack was stopped in the vestibule for thirty seconds to ensure consistent flash times while the clear coat bells were prepared for spray. During this time, the base coat film build panels were replaced with the two remaining cold-rolled steel panels (clear coat film build panels).
12. Clear coat was applied in two passes.
13. The clear coat film build, base coat + clear coat and clear coat only panels were removed from the panel rack and placed with the base coat film build panels in the oven at 93.3°C (200F) after a ten minute ambient flash time. As soon as the panels were in the oven, the temperature was raised to 143.9°C (291F). The panels were left to cure for 32 minutes.
14. The panels and the foils were removed from the oven. All four of the foils were weighed. The results were noted as W_F (final weight after cure).
15. The spray and dehydration solids contents were calculated.

$$\%\ Spray\ Solids = \frac{(W_F - W_{BS})}{(W_S - W_{BS})}$$

$$\%\ Dehydration\ Solids = \frac{(W_D - W_{BS})}{(W_S - W_{BS})}$$

16. The base coat and clear coat film builds were determined for both the horizontal and vertical surfaces using the Elcometer. A plastic template, with holes for the Elcometer probe placed 2.54 cm (1 inch) apart, was placed over the film build panel (Figure 21). Nine readings were taken (beginning at the top of the panel) and the average film build was recorded.

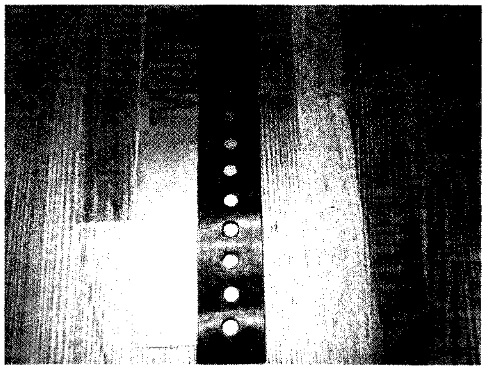


Figure 21 – Plastic film thickness template

17. The "clear coat only" and the "base coat + clear coat" panels for both the horizontal and vertical surfaces were measured using the wave-scan DOI. Each panel was measured five times. In each case, to ensure consistency between panels, the wave-scan was rolled across the surface of the panel in the direction that the paint was applied.
18. A screen shot of the environmental conditions for the booths was printed to verify that the proper settings were used for each run. An example of this printout is provided in Appendix I.

CHAPTER 5 – ANALYSIS OF DATA, RESULTS AND DISCUSSION

5.1 Panel Information Results

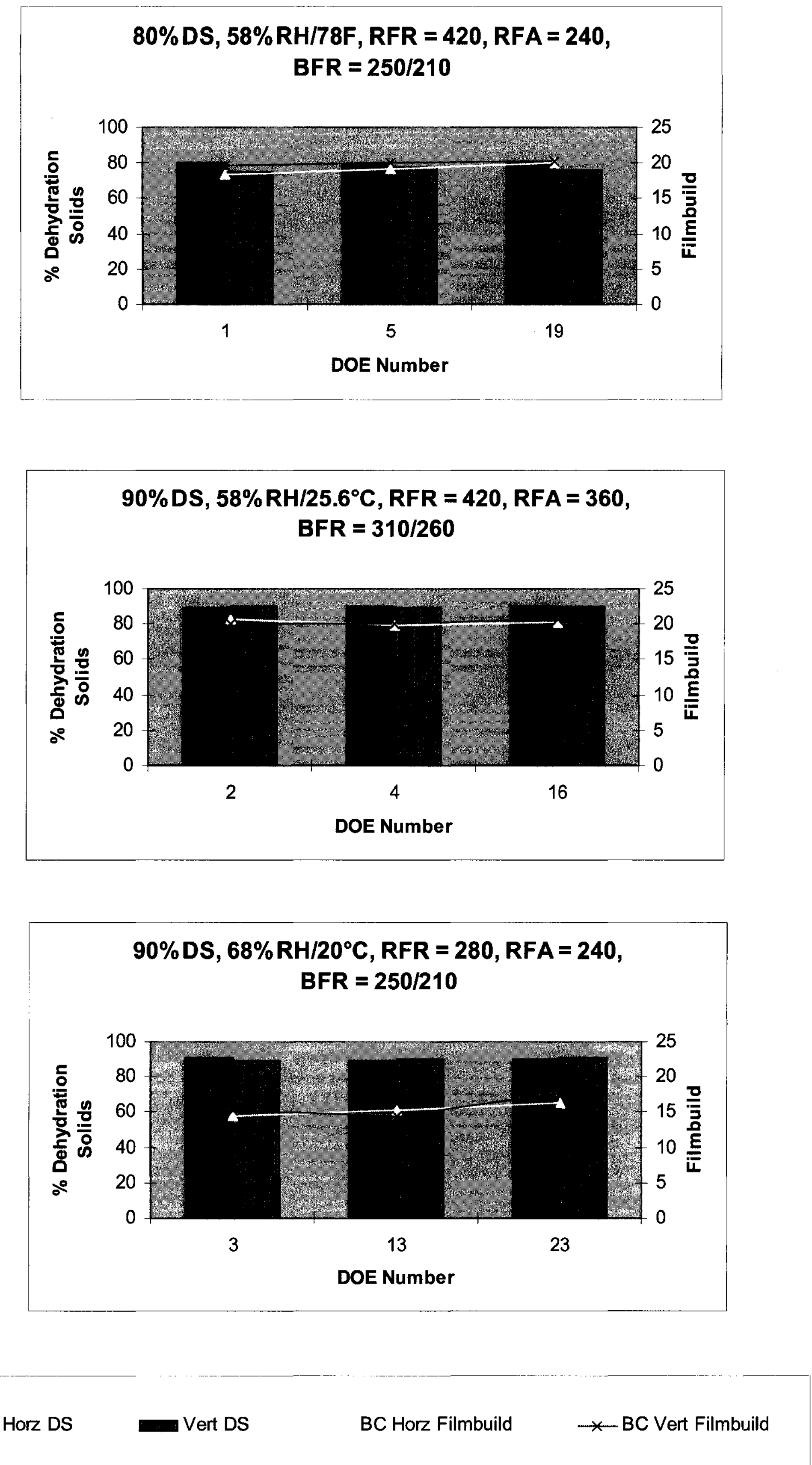
After each set of panels had been painted, spray and dehydration solids, base coat and clear coat film thicknesses and appearance element values were documented. The information was compiled into several spreadsheets for analysis. Initially, the DOE table was extended to include horizontal and vertical dehydration solids and base coat and clear coat horizontal and vertical film thicknesses. An excerpt of this table is given in Table 21 where DS represents dehydration solids, BC represents base coat and CC represents clear coat. Horz and Vert indicate horizontally and vertically sprayed panels, respectively and COV refers to the coefficient of variation within the replicate set. The information in the table was sorted to ensure that three replicates for each combination of variables in the DOE and five target replicates were adjacent. The dehydration solids and film thickness information were combined for each set of replicates and is represented graphically in Figure 22.

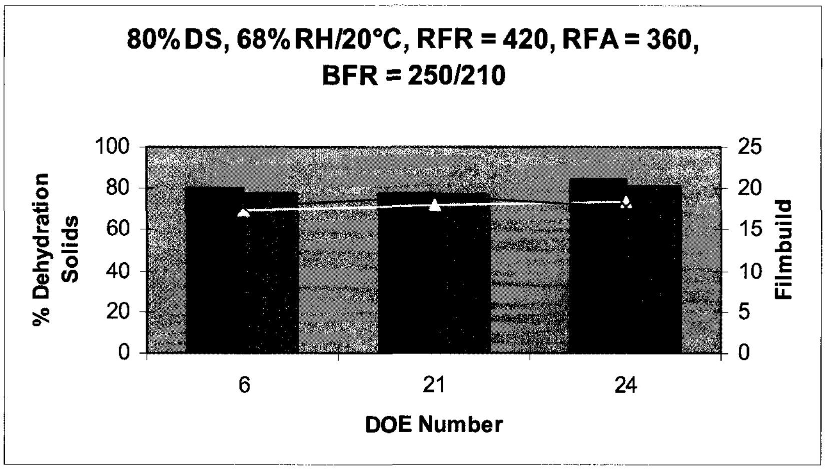
Each of the graphs in Figure 22 contain all the dehydration solid and film thickness information for a particular set of conditions as prescribed in the DOE. These graphs show the consistency in the process. The title indicates the conditions under which each replicate set was sprayed and the order in which the runs were completed was randomly assigned. For example, panels painted in Runs 1, 5 and 19 were all painted with environmental conditions of 58% relative humidity and a booth temperature of 25.6 °C (78F), they were dehydrated for three minutes at 82.2 °C (180F), the reciprocator flow rate was 420 cm^3/min, the reciprocator fan air was 240 L/min and the bell flow rate was 210 cm^3/min for the horizontal bell and 250 cm^3/min for the vertical bell. The percentages of dehydration solids achieved are represented by the bar graphs – dehydration solids on the horizontal panels are represented by the burgundy bars and dehydration solids on the vertical panels are represented by the blue bars. The film thicknesses are illustrated using a line graph. The yellow line represents the film

Table 21 – Dehydration solids and film thickness summary

Order	Horz DS (%)	Vert DS (%)	BC Horz Filmbuild (μm)	BC Vert Filmbuild (μm)	CC Horz Filmbuild (μm)	CC Vert Filmbuild (μm)
1	80	75	18.29	19.56	51.31	48.01
5	79	78	19.30	20.07	53.85	45.21
19	80	76	20.07	20.32	55.88	48.77
COV	**0.72**	**2.00**	**4.64**	**1.94**	**4.27**	**3.96**
2	89	90	20.57	20.07	56.39	44.96
4	90	89	19.81	20.07	61.98	46.99
16	90	90	20.32	20.57	56.39	42.16
COV	**0.64**	**0.64**	**1.92**	**1.45**	**5.54**	**5.42**
3	91	89	14.48	15.24	57.66	48.77
13	89	90	15.24	14.48	57.91	51.05
23	90	91	16.26	17.78	58.42	50.04
COV	**1.11**	**1.11**	**5.82**	**10.92**	**0.67**	**2.29**
6	80	78	17.27	17.78	56.39	48.77
21	78	77	18.03	19.05	54.10	51.56
24	84	81	18.29	17.78	59.94	49.78
COV	**3.79**	**2.65**	**2.96**	**4.03**	**5.18**	**2.83**
7	81	78	16.00	17.27	57.15	50.04
8	79	76	17.78	17.27	58.67	49.75
18	77	80	16.26	18.03	57.40	48.77
COV	**2.53**	**2.56**	**5.77**	**2.51**	**1.42**	**2.34**
9	90	89	14.22	15.24	60.45	46.74
11	91	90	14.22	14.48	55.88	44.45
15	90	90	14.73	15.75	59.94	44.96
COV	**0.64**	**0.64**	**2.04**	**4.22**	**4.26**	**2.65**
10	81	76	17.78	17.53	57.15	48.51
12	82	76	17.53	19.30	53.09	49.02
14	80	77	17.53	18.03	55.63	45.97
COV	**1.23**	**0.76**	**0.83**	**5.07**	**3.71**	**4.41**
17	89	89	21.34	22.61	54.61	49.28
20	90	90	21.08	20.83	54.36	50.04
22	89	86	21.59	21.34	52.83	44.45
COV	**0.65**	**2.36**	**1.19**	**4.24**	**1.78**	**6.32**
Target 1	83	85	16.51	16.26	60.96	49.28
Target 2	83	87	17.78	19.05	55.12	52.83
Target 3	89	88	19.05	18.80	58.17	47.75
Target 4	87	88	18.29	18.54	57.91	48.01
Target 5	90	89	16.26	17.27	54.10	48.26
COV	**3.80**	**1.74**	**6.73**	**6.58**	**4.74**	**4.26**

thickness on the horizontal panels while the turquoise line represents the film thickness on the vertical panels. Table 21 and Figure 22 represent the variation between replicates. The largest COV is 10.9%, which is for the base coat vertical filmbuild in Runs 3, 13 and 23. This is unusually high as the rest COVs for the base coat filmbuilds are consistently less than 7%. The dehydration solids values are even more consistent between replicates with all COVs less than 4%.


80% DS, 58% RH/78F, RFR = 420, RFA = 240,
BFR = 250/210
% Dehydration Solids
Filmbuild
DOE Number
1
5
19
90% DS, 58% RH/25.6°C, RFR = 420, RFA = 360,
BFR = 310/260
% Dehydration Solids
Filmbuild
DOE Number
2
4
16
90% DS, 68% RH/20°C, RFR = 280, RFA = 240,
BFR = 250/210
% Dehydration Solids
Filmbuild
DOE Number
3
13
23
Horz DS
Vert DS
BC Horz Filmbuild
BC Vert Filmbuild


80% DS, 68% RH/20°C, RFR = 420, RFA = 360, BFR = 250/210
% Dehydration Solids
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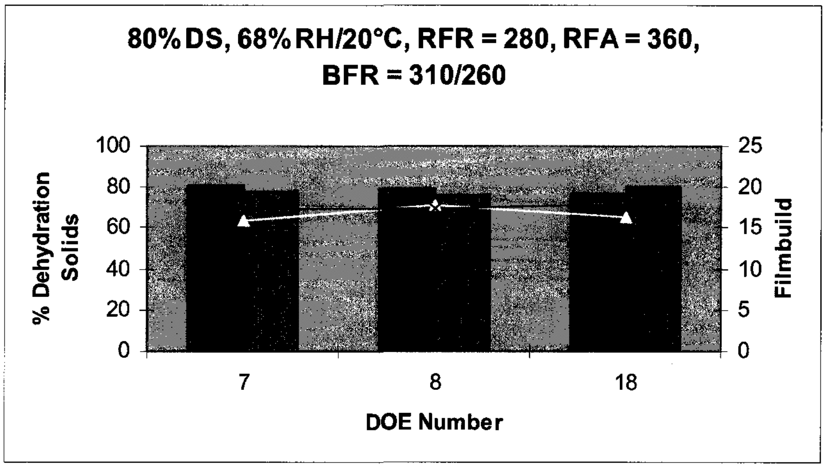
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% Dehydration Solids
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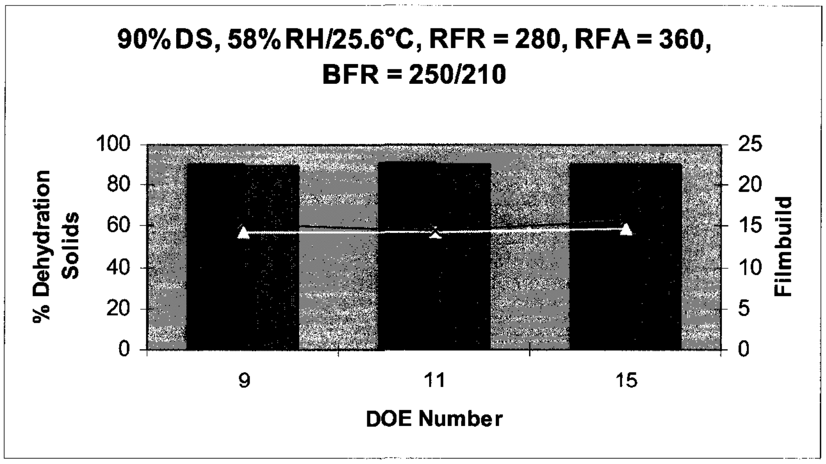
90% DS, 58% RH/25.6°C, RFR = 280, RFA = 360, BFR = 250/210
% Dehydration Solids
Filmbuild
DOE Number
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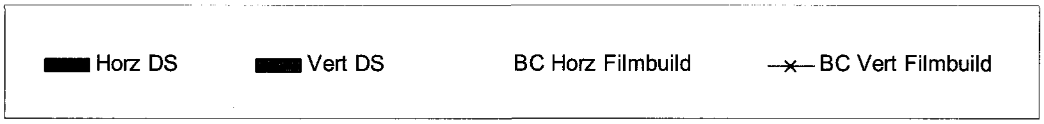
Horz DS
Vert DS
BC Horz Filmbuild
BC Vert Filmbuild

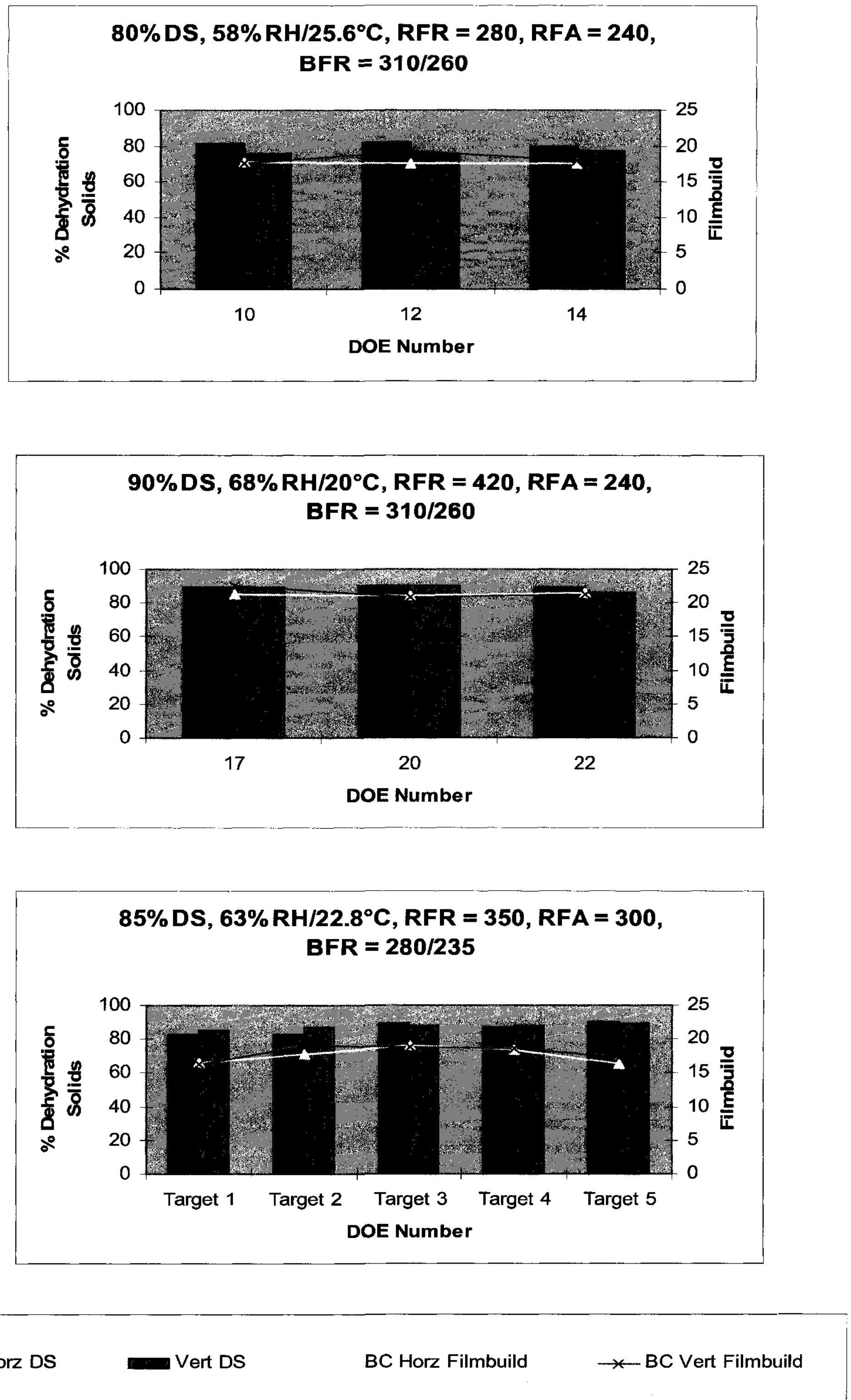

Figure 22 – Dehydration solids and film thickness results. Each graph represents one set of replicates. DS = dehydration solids, RFR = reciprocator flow rate, RFA = reciprocator fan air, BFR = bell flow rate

A final graph was prepared illustrating the change in clear coat film thickness over the duration of the experiment. Since clear coat film thickness was intended as a constant, it is important to verify that the set points for the clear coat equipment produced consistent results. The film thickness trends for both horizontal and vertical panels are shown in Figure 23. In this figure, the purple line illustrates the clear coat film thickness trend for vertically sprayed panels while the light blue line demonstrates the trend for the horizontally sprayed panels. The coefficient of variation for the horizontal film thickness is 4.55, while the coefficient of variation for the vertical film thickness is 5.03.

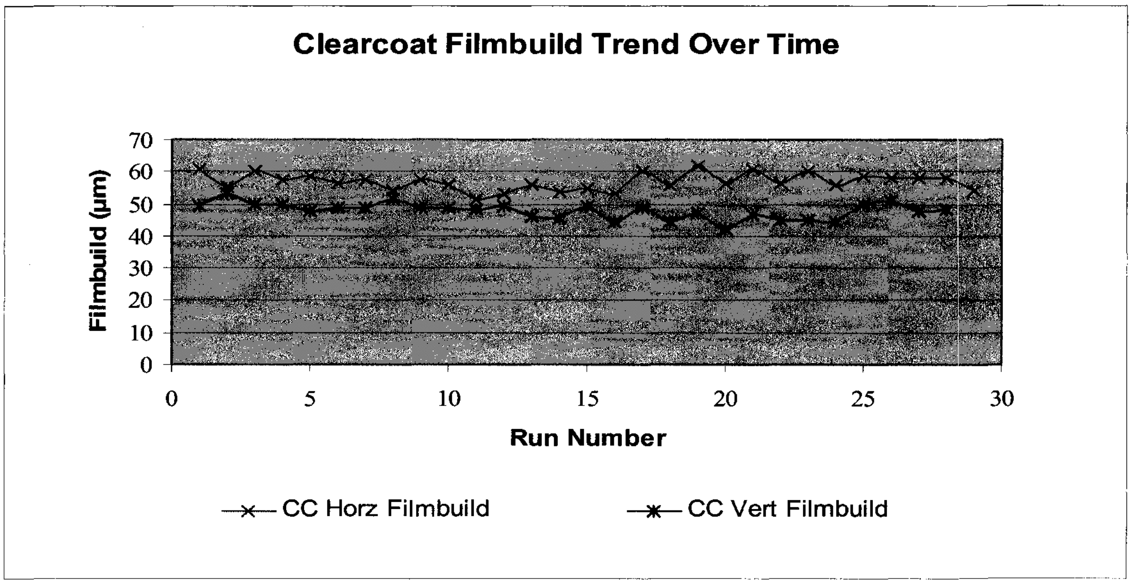

Figure 23 – Clear coat film thickness trend

5.2 wave-scan DOI Results

The appearance information generated by the wave-scan DOI was downloaded to a spreadsheet using the auto-chart software developed by BYK Gardner. It was then organized into tables according to the run number and orientation/material. Each panel was measured five times. The values generated for each appearance element were averaged and the coefficient of variation was calculated. An example of the readings for the first target run is provided in Table 22 and its structure spectrum is illustrated in Figure 24. The data and the graphs for all runs are provided in Appendix J.

Table 22 – Summary of appearance element data for target run 1

Target 1

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.7	13.8	29.3	14.2	14.0	10.6
Reading 2	6.7	12.4	26.5	13.2	13.1	4.7
Reading 3	5.6	10.4	23.6	10.7	10.9	7.0
Reading 4	4.6	10.0	22.3	11.2	12.3	7.1
Reading 5	6.0	10.4	21.6	11.6	13.1	8.5
Average	5.9	11.4	24.7	12.2	12.7	7.6
Cofficient of Variation	0.15	0.14	0.13	0.12	0.09	0.29

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.3	27.6	41.9	21.6	14.2	7.6
Reading 2	21.7	27.0	39.5	20.9	14.6	7.6
Reading 3	20.0	24.9	39.5	19.2	13.3	8.4
Reading 4	21.5	25.1	40.4	20.4	11.4	12.7
Reading 5	20.4	25.6	38.6	17.9	13.6	11.7
Average	21.2	26.0	40.0	20.0	13.4	9.6
Cofficient of Variation	0.04	0.05	0.03	0.07	0.09	0.25

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	10.5	25.2	17.3	17.7	13.1
Reading 2	5.8	10.3	22.3	16.8	18.7	10.4
Reading 3	5.3	9.9	23.6	16.3	18.6	6.5
Reading 4	5.9	10.8	23.9	15.1	16.4	6.4
Reading 5	6.6	9.7	22.3	15.7	15.8	6.1
Average	6.1	10.2	23.5	16.2	17.4	8.5
Cofficient of Variation	0.11	0.04	0.05	0.05	0.07	0.37

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.1	32.7	42.3	22.1	17.4	10.9
Reading 2	26.0	35.9	43.5	21.9	18.5	8.1
Reading 3	25.9	33.0	42.4	21.4	18.2	10.0
Reading 4	25.4	33.0	42.7	20.6	16.5	9.7
Reading 5	24.8	32.8	42.0	20.3	14.5	12.1
Average	25.4	33.5	42.6	21.3	17.0	10.2
Cofficient of Variation	0.02	0.04	0.01	0.04	0.09	0.15

Summary

H - CC	5.9	11.4	24.7	12.2	12.7	7.6
H - T	21.2	26.0	40.0	20.0	13.4	9.6
V - CC	6.1	10.2	23.5	16.2	17.4	8.5
V - T	25.4	33.5	42.6	21.3	17.0	10.2

Once the data had been organized for all the replicates in a particular group, graphs illustrating horizontal and vertical trends were prepared. Each graph shows the contrast value versus the structure spectrum element for the base coat + clear coat panel (square data points) and the clear coat only panel (diamond data points). Each target run is identified by a different colour. The remaining graphs can be found in Appendix J.

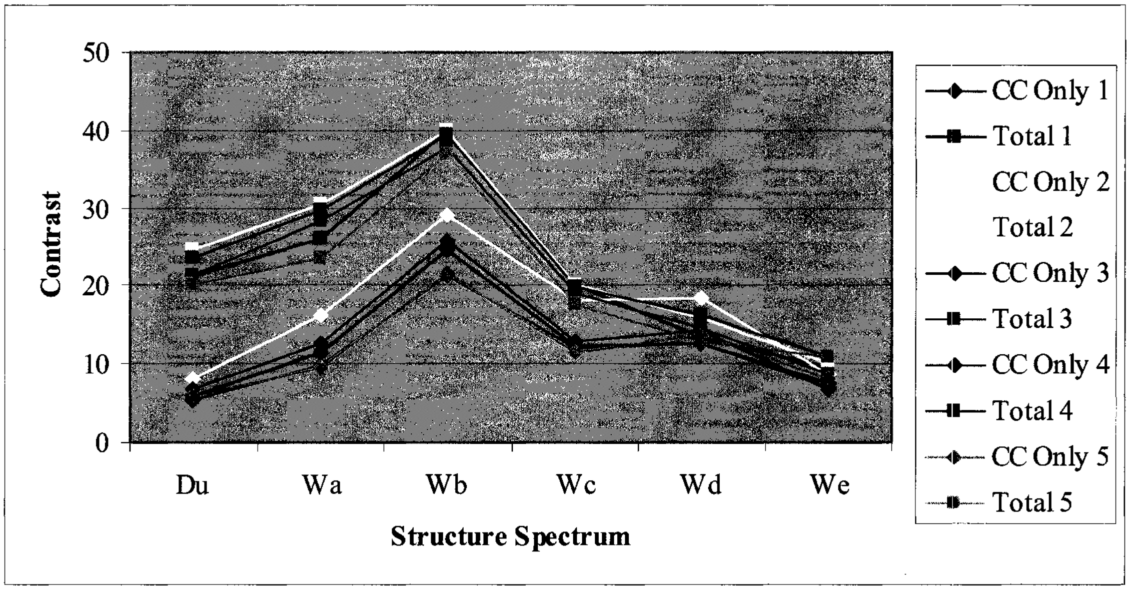

Figure 24 – Horizontal target trends (all 5 replicates shown)

Figure 24 suggests that approximately half of the contrast value is a result of the application of base coat and the other half is a result of the application of clear coat in the du, Wa and Wb portion of the structure spectrum. This observation is consistent with beliefs in the paint industry that base coat is responsible for the waviness found in the short wave region (du, Wa and Wb) of the structure spectrum. This figure also suggests that the application of clear coat is responsible for nearly all of the surface structures formed in the Wc, Wd and We portions of the structure spectrum.

5.3 wave-scan DOI Data Analysis

The averaged structure spectrum values calculated for horizontal and vertical clear coat only and base coat + clear coat panels were used to statistically analyze the impact of changing a process variable on the overall appearance. Linear regression analysis and ANOVA (Analysis of Variance) were completed using Minitab software. Normal Probability Plots of the Standardized Effects were plotted for each of the four sets of data, as shown in Appendix K. The normal probability plot of the standardized effects of du for the horizontal base coat + clear coat panels is provided in Figure 25. Each of the standardized effects is graphed and both individual effects and compound effects are shown on the graphs. All second order interactions were calculated and non-significant second order interactions were removed from the graphs to improve clarity. The solid blue line indicates where the points would be expected to fall if there were no effects. The red square data points indicate significant effects. The further the data point is from the trend line, the greater the standardized effect. Figure 25 indicates that dehydration solids influence the dullness characteristic of a panel.

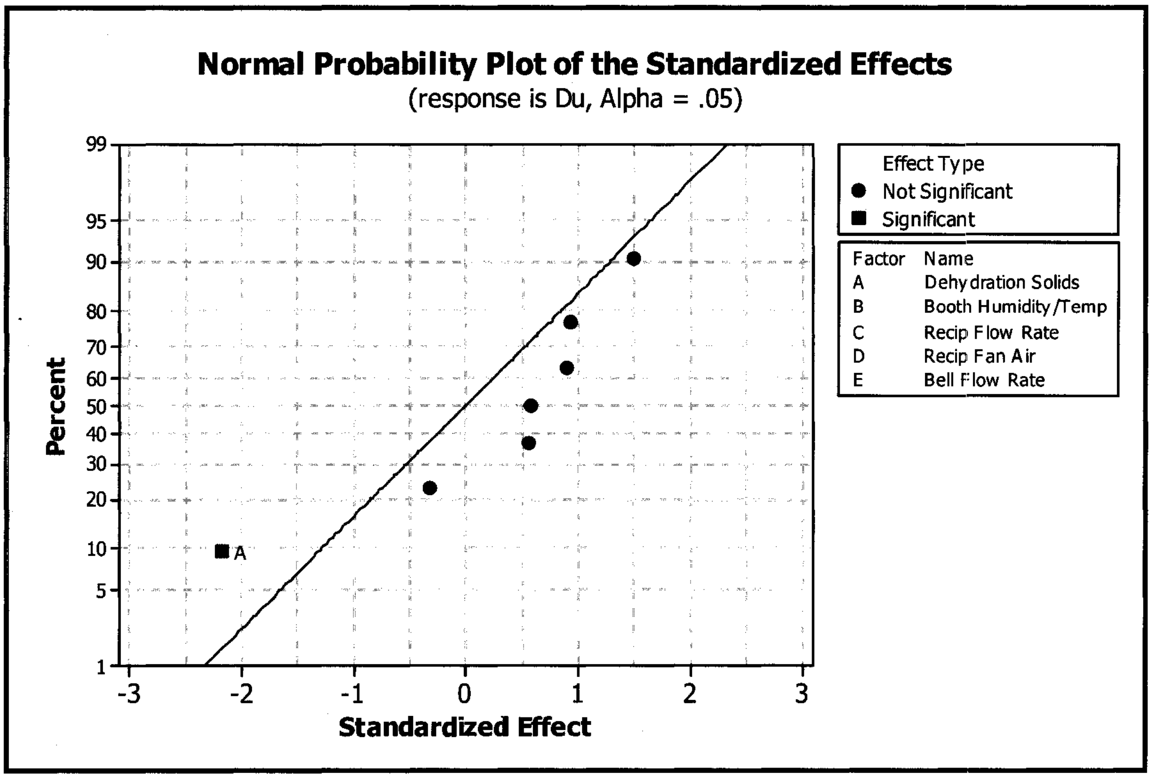

Figure 25 – Normal probability plot of the standardized effects for dullness

Further, the plot indicates the direction of the effect. Negative effects lie to the left of the line. As a result, increasing these variables from the low level to the high level creates a decreased response. Similarly, positive effects which lie to the right of the line create increased responses when the variable is increased from the low level to the high level. Since a decreased response (lower contrast) results in an improvement in appearance, any process parameter whose effect lies to the left of the line should be increased to improve the appearance element value. Conversely, process parameters whose effect lies to the right of the dividing line must be decreased to improve the appearance element.

Careful examination of the results of the normal probability plots (Appendix K) show that all of the process parameters chosen for the fractional factorial DOE had an impact on at least one element of appearance. Second order interactions were tested and two additional interactive effects were found: (booth humidity/temperature) x (reciprocator flow rate) and (booth humidity/temperature) x (bell flow rate). The impact of these interactions can be further tested using additional DOE. A summary of all the significant effects based on the normal probability plots is provided in Table 23.

Each combination of wave-scan DOI element and process parameter in Table 23 has four available entries shown by dividing the cell into four quadrants. In each cell, the upper left quadrant shows the effects for horizontal clear coat only panels, the upper right quadrant displays effects for horizontal base coat + clear coat panels, the lower left quadrant contains effects for vertical clear coat only panels and the lower right quadrant holds effects for vertical base coat + clear coat panels. In each case, an X indicates that the process parameter has a significant impact on the wave-scan DOI element. In addition, interactive effects are also indicated in the rightmost two columns where column headings contain two process parameters. For example, booth temperature/humidity and reciprocator flow rate combined had a significant effect on the Wb portion of the structure spectrum for the horizontal base coat + clear coat panel. Cells highlighted in red indicate effects negative effects, while cells highlighted in green indicate positive effects.

Table 23 illustrates that changing any of the process parameters or combinations of parameters does not have a significant effect on any of the appearance elements for any

Table 23 – Summary of normal probability plot effects

	Dehyd. Solids		Booth Temp /Humidity		Recip. Flow Rate		Recip. Fan Air		Bell Flow Rate		Booth Temp /Humidity & Recip. Flow Rate		Booth Temp /Humidity & Bell Flow Rate	
Du														
W_a														
W_b														
W_c														
W_d														
W_e														

Legend:

	CC Only	Total
Horz		
Vert		

X = significant effect

decrease parameter to improve appearance

increase parameter to improve appearance of the vertical clear coat only panels. In addition, only variations in booth humidity/temperature alone or in combination with changes in the bell or reciprocator flow rate have a significant effect on the appearance elements for horizontal clear coat only panels. Neglecting changes in We, these effects tend to occur on appearance elements with shorter wavelengths (du, Wa, Wb). These results can be expected since the only process parameter changed that affects clear coat application was booth humidity/temperature. Apart from this, none of the effects found from the application of base coat influenced the appearance of clear coat.

The base coat + clear coat panels are affected by dehydration solids, reciprocator flow rate and bell flow rate the most, with dehydration solids affecting at least the horizontal base coat + clear coat panel or the vertical base coat + clear coat panel for each of the appearance elements. Except for Wd, increasing the dehydration solids results in improved appearance. It should also be noted that the dullness characteristic (du) is only influenced by dehydration solids. Wa is affected by dehydration solids and reciprocator flow rate (vertical panels) and bell flow rate (horizontal and vertical panels), which in contrast to dehydration solids, must be decreased to improve appearance. Wb and Wc are affected at least once (horizontal or vertical) by each of the process parameters. Wb is also affected by both interactions of process parameters – (booth humidity/temperature) x (reciprocator flow rate) and (booth humidity/temperature) x (bell flow rate). This result differs from the findings of the preliminary study where Wb was found to be least likely to be affected by the process. In some cases, a combination of process parameter and appearance element indicates a significant effect for the clear coat only panel and the base coat + clear coat panel.

Table 23 also points out the polarity of the process parameters. A quick glance at the table verifies that each process parameter affects all appearance elements in the same manner with the exception of booth humidity/temperature and dehydration solids. For example, reciprocator fan air must always be increased to improve appearance and bell flow rate must always be decreased to improve appearance. It should be noted that to improve appearance, the clear coat booth humidity/temperature should be increased while the base coat booth humidity/temperature should be decreased. Also, the interaction of booth humidity/temperature with reciprocator and bell flow rates should be increased to improve appearance. Since in these experiments the base coat and the clear coat booth humidity/temperatures were adjusted simultaneously, the clear coat booth humidity/temperature is responsible for the significant impacts on the appearance elements on the clear coat only panels while the base coat humidity/temperature is responsible for the significant impacts on the appearance elements on the base coat + clear coat panels; but the effect on the base coat outweighs the effect on the clear coat.

Finally, it is surprising to note that the appearance elements are affected approximately the same number of times for both horizontal and vertical panels. Gravitational forces are identified in literature as having a significant impact on the flowing/leveling characteristics of the coating. However, different film thickness specifications for horizontally and vertically coated surfaces in these experiments may account for this conclusion.

In theory, increasing the dehydration solids allows the formation of a drier surface for the application of clear coat, reducing interlayer mixing and "soak in" of the clear coat. A more distinct interface between clear coat and base coat allows for more refraction and increases the gloss. This mechanism explains how a higher level of dehydration solids leads to improved du. The other elements may be reduced with higher dehydration solids due to improved leveling in the dehydration oven. This result is consistent with DuPont's requirement for higher dehydration solids contents for metallic paints than other non-metallic paints. This manufacturer also has a higher dehydration solids content requirement than other automotive coatings suppliers, such as PPG or BASF.

The results also indicate that the booth humidity/temperature should be increased in the clear coat zone. The high level for this parameter actually has high humidity and low temperature (68%RH/68F). In the base coat zone, the results suggest decreasing the booth humidity/temperature to the low level (58%RH/78F) which consists of low humidity and high temperature, producing a slightly drier application condition. Similar to higher dehydration solids, a slightly drier application condition should produce an improved appearance. However, for solventborne clear coat, the drier condition may be too dry and does not allow adequate time for the coating to level.

At the levels tested, decreasing the reciprocator flow rate results in less paint particles being sprayed per time. At the same level of atomization air, the paint sprayed at the decreased flow rate is better atomized which results in smaller paint particles, more in-flight evaporation of solvent and improved appearance. The same is true for bell flow rate. At the same level of bell speed, the paint sprayed at the decreased flow rate is better atomized resulting in improved appearance.

Finally, at the levels tested, increasing the reciprocator fan air creates a more concentrated stream of paint particles as the pattern is narrowed. This produces a wetter application, unless the fan air is aiding atomization or increasing the impact speed of the paint particles on the surface, resulting in better leveling and improved appearance.

Many of the observations noted from the normal probability plots indicate that an improvement in appearance will be achieved through a slightly drier application. Several sources from the literature review suggest that increased leveling, achieved through a wetter application, will improve appearance. However, another study conducted at the ACRF, using a DuPont material also concluded that drier conditions result in better appearance. This suggests that further study of application characteristics such as droplet size, time-of-flight and leveling during drying are needed to fully understand the phenomena occurring during paint application so that optimal cure conditions can be determined.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study involved determining the effect of various topcoat process parameters on elements of appearance. It is important to note that PPG materials were used to coat the directional colour DOE panels used in the initial statistical analysis, PPG clear coat (DCT 5555) was used in the clear coat film thickness study, while DuPont materials (DA4 base coat and RK-8064 clear coat) were used in the fractional factorial investigation.

Several substrates were initially considered. A profilometer and a dry film thickness gauge were used to determine that dipped electro-coated panels had smooth and more consistent surfaces than coil-coated aluminum and spray-primed panels.

Statistical analysis, including t-test and regression analysis, of a preliminary experiment which contained ten sets of directional colour DOE panels sprayed by PPG, indicated that paint age, dehydration solids, reciprocator flow rate, reciprocator fan air, bell flow rate and clear coat film thickness had the most impact on appearance elements measured by the wave-scan DOI instrument. This analysis also suggests that the Wb appearance element is least likely to be affected by process parameters.

A separate clear coat film thickness versus appearance element study was conducted by the staff at the ACRF. Analysis of the results of this study found strong relationships between Wa, Wb, Wc and Wd elements and clear coat film thickness. It was found that Wb and Wc elements on both horizontally and vertically sprayed panels and the Wa element on vertically sprayed panels had optimal appearance values when the clear coat film thickness was approximately 35 – 38 μm (1.6 mils). In addition, the Wa element on horizontally sprayed panels and the Wd element on both horizontally and vertically sprayed panels had continually improving appearance values as the clear coat film thickness increased. The thickest film tested was approximately 60 μm (2.6 mils), so an optimum may exist above this value for Wa and Wd.

The results from a ¼ fraction factorial DOE on dehydration solids, booth temperature/humidity, reciprocator flow rate, reciprocator fan air and bell flow rate were analyzed using linear regression analysis and ANOVA. Careful examination of the Normal Probability Plot of the Standardized Effects show that each of the process parameters investigated had an effect on at least one of the appearance elements measured by the wave-scan DOI. These plots also highlighted two interactive effects: (booth humidity/temperature) x (reciprocator flow rate) and (booth humidity/temperature) x (bell flow rate).

The clear coat only panels were used to verify that the application of clear coat does not impact the effects of process parameters on base coat appearance. It was found that the vertical clear coat only panels were not affected by any of the process parameters investigated, while the horizontal clear coat only panels were affected only by clear coat booth humidity/temperature.

The appearance elements for the base coat + clear coat panels were affected by each of the process parameters investigated at least once. Appearance elements were affected approximately the same number of times for both horizontally and vertically sprayed panels, even though literature and physics suggest that gravity, which affects horizontal surfaces more than vertical surfaces, is an important factor in the flowing/leveling characteristic of coatings. Some process variables were found to affect an appearance element for both horizontal and vertical surfaces. This is true for the dehydration solids affecting dullness and Wc, reciprocator flow rate affecting Wb and Wc and bell flow rate affecting Wa. In addition, Wb is affected by the combination of booth humidity/temperature and bell flow rate.

In the preliminary study, it was found that dehydration solids were responsible for nearly 50% of the impacts on appearance caused by process parameters. The subsequent study indicates that dehydration solids were responsible for 75% of the appearance impacts on dullness and nearly 33% of the impacts on any of the appearance elements. Unlike the preliminary study, this study found that Wb was affected by three of the five process parameters tested (booth humidity/temperature, reciprocator flow rate and reciprocator fan air) and both of the process parameter interactions.

In general, to improve appearance, it is necessary to increase clear coat film thickness, dehydration solids and reciprocator fan air and decrease bell flow rate and reciprocator flow rate. This conclusion, in general, supports a drier application procedure, whereas the literature suggests that a wet application enhances leveling and result in a smoother finish. However, other studies conducted at the ACRF using DuPont materials have shown that a drier application results in improved appearance.

6.2 Recommendations

- The current study used two levels (high and low) to investigate whether or not changing a process parameter had an effect on the appearance of a painted surface. It would be beneficial to perform further studies on each significant variable, one at a time as was done in the clear coat film thickness study.
- It is recommended that this study be repeated with different base coats manufactured by DuPont as well as base coats from other manufacturers to validate and generalize the findings of this study.
- The panels in this study were coated using a two-pass base coat application system. At the ACRF, bells apply the first coat and reciprocators apply the second coat. Some systems utilize a bell-bell process where bells apply both coats of paint. It would be beneficial to observe whether or not the findings in this study are valid for a bell-bell process.
- In this study, several process parameters thought to impact appearance were investigated. It would be beneficial to study the impact of changing process parameters not considered in this study, such as paint age, electrostatic voltage and atomization/particle size as well as process parameters not involved in the topcoat process such as pretreatment process parameters (e-coat thickness, metal substrate) and material properties (viscosity, solids content).

- Since overall appearance can be dependant on the roughness of the substrate, this study used dipped electro-coated appearance panels which were found to have the smoothest, most consistent surface. This is not representative of a typical layering system and it would be advantageous to investigate the effects of process parameters on appearance panels which follow the typical DaimlerChrysler layering system.
- This study screened the application process for parameters having an influence on appearance. In addition, at the levels tested, the "direction" which leads to an improved appearance was also discovered. Further studies should be conducted to determine the values of these process parameters which result in optimal appearance values. This may be achieved using full factorial or surface response design of experiments.
- For the purposes of controlling cost, 25.4 μm x 25.4 μm (10 inch x 10 inch) appearance panels were used. It is possible that appearance may change over larger areas and/or curved locations on a vehicle. For this reason, it would be beneficial to repeat these studies on whole vehicles.

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APPENDICES

APPENDIX A – PRELIMINARY STUDY T-TEST and REGRESSION SUMMARY DATA

BB8 Horizontal Results

B8 Horizontal

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	T,R	T,R	R			
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						T,R
Clearcoat Thickness					T,R	
Bell Shaping Air				R		
Bell Speed						
Recip Fan Air						
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Du, Wa
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	We
Clearcoat Thickness	Wd
Bell Shaping Air	
Bell Speed	
Recip Fan Air	
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	1.7	0.0	0.3	7.8	3.2	7.4
Paint Fluidity	3.9	2.5	1.6	2.6	8.9	3.5
Dehydration Solids	[redacted]	[redacted]	[redacted]	4.6	16.2	15.4
Booth Humidity/Temperature	8.6	9.1	4.8	0.1	1.3	0.4
Recip Atomizing Air	7.1	10.3	2.9	18.0	11.2	0.8
Recip Flow Rate	0.0	7.9	22.6	12.8	3.1	[redacted]
Clearcoat Thickness	11.8	7.0	0.0	22.8	[redacted]	13.3
Bell Shaping Air	0.0	6.3	20.4	[redacted]	9.0	0.1
Bell Speed	0.1	0.1	11.1	2.6	1.9	1.0
Recip Fan Air	0.5	0.1	0.0	5.1	9.3	3.2
Bell Flow Rate	0.0	0.0	5.0	4.8	5.4	4.3

BB8 Vertical Panels

B8 - Vertical

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	T,R	T				
Booth Humidity/Temperature						T,R
Recip Atomizing Air						
Recip Flow Rate					T,R	
Clearcoat Thickness		R				
Bell Shaping Air			T			
Bell Speed						
Recip Fan Air						
Bell Flow Rate				T,R		T

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In both the multiple R and the R-squared tables, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. In both tables, either the multiple R value or the R-squared value for the regression without a specific process parameter was subtracted from the multiple R value or R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Du, Wa
Booth Humidity/Temp	We
Recip Atomizing Air	
Recip Flow Rate	Wd
Clearcoat Thickness	
Bell Shaping Air	Wb
Bell Speed	
Recip Fan Air	
Bell Flow Rate	Wc,We

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	0.0	0.1	1.8	6.7	2.0	12.9
Paint Fluidity	8.5	11.7	3.8	2.1	0.6	0.4
Dehydration Solids	[illegible]	19.5	1.4	4.1	3.0	1.5
Booth Humidity/Temperature	4.2	3.5	6.6	8.8	10.6	[illegible]
Recip Atomizing Air	0.4	0.3	0.6	12.9	6.4	0.1
Recip Flow Rate	16.2	16.4	11.2	8.1	[illegible]	14.6
Clearcoat Thickness	20.9	[illegible]	1.3	23.4	16.7	10.1
Bell Shaping Air	0.3	1.5	14.8	15.1	11.4	6.3
Bell Speed	0.2	0.0	22.0	0.6	4.2	0.3
Recip Fan Air	12.5	13.6	0.2	3.7	0.0	1.6
Bell Flow Rate	6.5	5.1	17.7	[illegible]	7.3	0.1

CB6 Horizontal Panels

CB6 - Horizontal

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	T,R	T,R			R	
Paint Fluidity						T,R
Dehydration Solids			T,R	T		
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness	R				T,R	
Bell Shaping Air						
Bell Speed						
Recip Fan Air						
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	Du, Wa
Paint Fluidity	We
Dehydration Solids	Wb,Wc
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	Wd
Bell Shaping Air	
Bell Speed	
Recip Fan Air	
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	[redacted]	[redacted]	0.7	0.0	[redacted]	19.1
Paint Fluidity	0.3	0.6	9.3	1.4	1.3	[redacted]
Dehydration Solids	1.7	15.6	[redacted]	21.9	4.0	4.2
Booth Humidity/Temperature	1.0	2.3	2.5	0.5	0.5	0.1
Recip Atomizing Air	3.7	6.1	7.0	12.3	10.2	5.2
Recip Flow Rate	7.6	2.8	9.1	15.7	4.9	6.1
Clearcoat Thickness	[redacted]	15.7	4.5	10.8	[redacted]	1.2
Bell Shaping Air	15.0	15.3	15.1	20.9	15.3	2.8
Bell Speed	0.8	0.5	3.6	0.7	0.0	12.7
Recip Fan Air	7.5	0.4	0.0	0.2	0.3	0.5
Bell Flow Rate	1.0	0.1	0.8	1.3	1.9	5.0

CB6 Vertical Panels

CB6 - Vertical

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids				T		
Booth Humidity/Temperature						
Recip Atomizing Air			T,R			
Recip Flow Rate					T,R	
Clearcoat Thickness				T,R		
Bell Shaping Air						T,R
Bell Speed					R	T
Recip Fan Air	T,R					
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Wc
Booth Humidity/Temp	
Recip Atomizing Air	Wb
Recip Flow Rate	Wd
Clearcoat Thickness	Wc
Bell Shaping Air	We
Bell Speed	We
Recip Fan Air	Du
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	5.8	22.2	18.9	7.5	0.7	19.0
Paint Fluidity	0.5	13.2	0.1	5.4	0.1	0.4
Dehydration Solids	14.1	14.2	14.3	14.6	0.0	3.8
Booth Humidity/Temperature	3.0	8.4	4.1	0.2	1.1	2.1
Recip Atomizing Air	1.8	5.0	[redacted]	20.1	0.0	5.1
Recip Flow Rate	6.2	4.4	0.1	5.3	[redacted]	0.5
Clearcoat Thickness	1.4	0.3	5.0	[redacted]	19.6	0.1
Bell Shaping Air	0.6	6.8	14.8	3.4	10.1	[redacted]
Bell Speed	5.8	6.5	2.1	19.3	[redacted]	23.9
Recip Fan Air	[redacted]	4.4	0.5	0.0	1.5	0.5
Bell Flow Rate	8.3	1.2	14.4	6.2	0.1	0.5

BPK Horizontal Panels

PK - Horizontal

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	T		T			
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness					T	T
Bell Shaping Air						
Bell Speed						
Recip Fan Air						
Bell Flow Rate		T				

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	Du,Wb
Dehydration Solids	
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	Wd,We
Bell Shaping Air	
Bell Speed	
Recip Fan Air	
Bell Flow Rate	Wa

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

BPK Vertical Panels

PK - Vertical

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	T					T
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness		T,R		T,R		T
Bell Shaping Air						
Bell Speed				R		
Recip Fan Air						
Bell Flow Rate	R	R				

Significance in Regression = R
Significance in T-test = T

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Du,We
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	Wa,Wc,We
Bell Shaping Air	
Bell Speed	
Recip Fan Air	
Bell Flow Rate	

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	23.8	24.6	6.7	18.1	11.7	7.7
Paint Fluidity	5.0	0.0	17.3	1.6	10.9	0.7
Dehydration Solids	17.0	5.8	0.1	0.8	4.2	24.2
Booth Humidity/Temperature	1.2	6.9	14.0	0.3	9.8	6.0
Recip Atomizing Air	2.3	0.0	7.9	13.1	11.5	1.1
Recip Flow Rate	0.7	4.0	5.3	0.2	6.5	2.6
Clearcoat Thickness	13.4	[redacted]	18.1	[redacted]	18.3	24.7
Bell Shaping Air	0.2	0.9	4.2	2.7	9.8	0.6
Bell Speed	1.8	1.7	0.6	[redacted]	2.6	4.1
Recip Fan Air	0.4	0.9	0.0	9.1	0.0	0.4
Bell Flow Rate	[redacted]		6.7	13.6	0.9	0.7

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process paramcters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

DBM Horizontal Panels

DBM - Horizontal

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age			T,R	T,R		T,R
Paint Fluidity						
Dehydration Solids				R	R	
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness						
Bell Shaping Air						
Bell Speed						
Recip Fan Air	T,R	T,R			T,R	
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	Wb, Wc, We
Paint Fluidity	
Dehydration Solids	
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	
Bell Shaping Air	
Bell Speed	
Recip Fan Air	Du, Wa, Wd
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	1.6	2.6	[illegible]	[illegible]	1.1	[illegible]
Paint Fluidity	0.3	0.1	6.8	3.0	0.0	0.3
Dehydration Solids	2.9	1.4	23.3	[illegible]	[illegible]	18.2
Booth Humidity/Temperature	11.6	10.1	1.9	1.9	0.1	4.0
Recip Atomizing Air	0.3	1.9	0.9	1.8	2.9	4.4
Recip Flow Rate	4.4	18.2	7.7	6.8	2.9	5.6
Clearcoat Thickness	0.4	0.3	1.2	6.3	12.5	8.4
Bell Shaping Air	10.5	0.2	3.1	1.0	3.9	2.9
Bell Speed	12.9	0.1	0.4	0.6	0.2	5.5
Recip Fan Air	[illegible]	[illegible]	7.8	2.8	[illegible]	4.7
Bell Flow Rate	0.2	6.6	13.5	16.2	5.4	14.9

DBM Vertical Panels

DBM - Vertical

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids			R		T,R	T,R
Booth Humidity/Temperature				T,R		
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness						
Bell Shaping Air						
Bell Speed						
Recip Fan Air	T,R	R				
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Wd, We
Booth Humidity/Temp	Wc
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	
Bell Shaping Air	
Bell Speed	
Recip Fan Air	Du
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	0.2	0.1	5.9	1.5	1.2	2.1
Paint Fluidity	0.0	0.7	5.6	8.9	0.4	0.0
Dehydration Solids	19.6	22.9	[redacted]	17.5	[redacted]	[redacted]
Booth Humidity/Temperature	13.8	14.1	24.9	[redacted]	23.3	16.9
Recip Atomizing Air	0.1	0.4	0.1	1.4	2.2	0.6
Recip Flow Rate	5.7	11.5	6.9	0.3	0.1	1.2
Clearcoat Thickness	4.4	4.3	6.1	15.0	17.3	4.5
Bell Shaping Air	1.1	14.3	10.0	1.6	0.3	5.2
Bell Speed	12.5	3.7	5.2	2.4	7.5	0.1
Recip Fan Air	[redacted]	[redacted]	0.4	0.4	0.5	4.8
Bell Flow Rate	12.1	17.7	15.3	8.2	10.7	23.3

DA4 Horizontal Panels

DA4 - Horizontal

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids	R	T,R	T,R	T,R	T,R	
Booth Humidity/Temperature						
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness						
Bell Shaping Air	R					
Bell Speed						
Recip Fan Air				R		T,R
Bell Flow Rate						

Significance in Regression = R
Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Wa, Wb, Wc, Wd
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	
Bell Shaping Air	
Bell Speed	
Recip Fan Air	We
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	1.0	0.5	0.1	2.6	12.5	0.4
Paint Fluidity	0.0	5.0	0.7	0.1	1.8	0.7
Dehydration Solids	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	23.7
Booth Humidity/Temperature	3.5	5.8	0.5	4.9	5.9	5.8
Recip Atomizing Air	0.1	6.1	0.6	0.1	0.5	0.7
Recip Flow Rate	3.7	0.7	0.2	4.7	8.5	2.2
Clearcoat Thickness	6.9	2.4	2.6	2.8	5.7	2.1
Bell Shaping Air	[redacted]	18.1	4.9	1.9	10.1	7.7
Bell Speed	9.4	3.3	0.0	4.7	13.5	8.3
Recip Fan Air	0.3	0.0	20.7	[redacted]	3.3	[redacted]
Bell Flow Rate	12.4	4.3	6.5	5.6	4.2	3.2

DA4 Vertical Panels

DA4 - Vertical

Summary Table

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age						
Paint Fluidity						
Dehydration Solids			R	T,R	T,R	T,R
Booth Humidity/Temperature					R	
Recip Atomizing Air						
Recip Flow Rate						
Clearcoat Thickness						
Bell Shaping Air						
Bell Speed						
Recip Fan Air		T,R				
Bell Flow Rate					R	

Significance in Regression = R

Significance in T-test = T

Note: T-test results table shows for a particular process parameter, which appearance elements were significant

Note: In the R-squared table, the regression was completed first with all the variables in the DOE. Each subsequent regression contained one less variable. The values in the matrix represent the influence of a particular process parameter on the appearance element. The R-squared value for the regression without a specific process parameter was subtracted from the R-squared value with all the process parameters and converted to a percentage. A 25% cutoff value was selected and those process parameters which influence an appearance element greater than 25% are highlighted red. Yellow highlighted squares indicated between 20 and 24.9% influence. Also, the most influential process parameter for a particular appearance element is indicated by a bolded frame.

T-test Results

Summary	T-test
Paint Age	
Paint Fluidity	
Dehydration Solids	Wc,Wd,We
Booth Humidity/Temp	
Recip Atomizing Air	
Recip Flow Rate	
Clearcoat Thickness	
Bell Shaping Air	
Bell Speed	
Recip Fan Air	Wa
Bell Flow Rate	

R-Squared

Influence of Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	0.2	3.2	1.5	0.3	0.5	15.5
Paint Fluidity	1.6	0.6	0.1	1.4	0.0	7.4
Dehydration Solids	18.9	16.9				
Booth Humidity/Temperature	3.8	1.8	0.4	15.0		0.9
Recip Atomizing Air	0.2	1.5	2.0	0.2	3.5	1.3
Recip Flow Rate	0.7	0.8	0.5	2.1	0.0	0.2
Clearcoat Thickness	0.0	4.8	2.2	0.6	3.5	11.6
Bell Shaping Air	8.1	0.8	0.0	0.1	0.6	7.1
Bell Speed	22.2	0.5	0.5	15.5	12.5	10.1
Recip Fan Air	18.1		13.9	15.1	0.2	9.1
Bell Flow Rate	18.2	3.1	4.3	7.2		0.1

T-test Result Summary (all data)

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	1	1	1	1		1
Paint Fluidity						1
Dehydration Solids	4	3	3	4	3	3
Booth Humidity/Temperature				1		1
Recip Atomizing Air			1			
Recip Flow Rate					2	1
Clearcoat Thickness		1		2	3	2
Bell Shaping Air						1
Bell Speed						1
Recip Fan Air	3	2			1	1
Bell Flow Rate		1		1		1

Regression Result Summary (all data)

Variable	Du	Wa	Wb	Wc	Wd	We
Paint Age	1	1	1	1	1	1
Paint Fluidity						1
Dehydration Solids	3	2	5	3	4	2
Booth Humidity/Temperature				1	1	1
Recip Atomizing Air			1			
Recip Flow Rate					2	1
Clearcoat Thickness	1	2		2	2	
Bell Shaping Air	1			1		1
Bell Speed				1	1	
Recip Fan Air	3	3		1	1	1
Bell Flow Rate	1	1		1	1	

Regression Results for Variables to be Further Investigated – Dehydration solids, booth humidity/temperature, reciprocator flow rate, bell flow rate, reciprocator fan air and clear coat film thickness

Adjusted R - All Variables

Summary	Du	Wa	Wb	Wc	Wd	We
DA4 Horizontal		0.67	0.91	0.89		0.83
DA4 Vertical	0.65	0.93	0.87	0.82	0.82	0.91
DBM Horizontal	0.73	0.91		0.65	0.80	
DBM Vertical	0.86	0.81	0.71	0.85	0.86	0.89
BPK Horizontal	no target data available					
BPK Vertical		0.71				0.77
CB6 Horizontal						
CB6 Vertical	0.79					
BB8 Horizontal	0.79	0.78				
BB8 Vertical	0.90	0.84			0.73	0.80

APPENDIX B – PROJECT SETUP PARAMETERS: CLEARCOAT FILM THICKNESS STUDY

Project 30 - Clearcoat Trials (PPG)

C3 - Basecoat Bells		C3 - Basecoat Robots		C3 - Clearcoat Bells	
				Clearcoat - DCT 5555	
BC Bell Zone Settings		**BC Robot Zone Settings**		**CC Bell Zone Settings**	
Temperature:		**Temperature:**		**Temperature:**	80F
Humidity:		**Humidity:**		**Humidity:**	50%
Filmbuild Specification:		**Filmbuild Specification:**		**Filmbuild Specification:**	2.0 mils
BC Bell Program Settings		**BC Robot Program Settings**		**CC Bell Program Settings**	
Style:		**Style:**		**Style:**	28
Colour:		**Colour:**		**Colour:**	3
Option:		**Option:**		**Option:**	1
Line Speed:		**Line Speed:**		**Line Speed:**	9 fpm
# Passes:		**# Passes:**		**# Passes:**	2
Target Distance:		**Target Distance:**		**Target Distance:**	10"
BC Bell Brush Files		**BC Robot Brush Files**		**CC Bell Brush Files**	
Vertical - Flow Rate:		**Vertical - Flow Rate:**		**Vertical - Flow Rate:**	225
Shaping Air:		**Fan Air:**		**Shaping Air:**	220
High Voltage:		**Atomizing Air:**		**High Voltage:**	90
Bell Speed:		**Tip Speed:**		**Bell Speed:**	400
		Restrictor Size:			
				Horizontal - Flow Rate:	245
				Shaping Air:	235
				High Voltage:	90
				Bell Speed:	400

Note: Bell 3-2 is used to spray horizontal panels and Bell 1-2 is used to spray vertical panels in clearcoat.

Project 30 - Clearcoat Trials (PPG)

Conveyor Settings:

Zone	Line Speed (fpm)	Flash Time (s)	Delay Timers (s)
B/C Manual	-	-	-
B/C Bell	-	-	3
B/C Robot	-		3
B/C Vestibule	-	-	3
Electric IR	-		3
Convection	-	-	3
C/C Vestibule	-	-	75
C/C Bell	9.0		3
C/C Reverse	59.0		3
C/C Manual	59.0		40

Dehydration Oven Settings:

Temperature:
Solids:

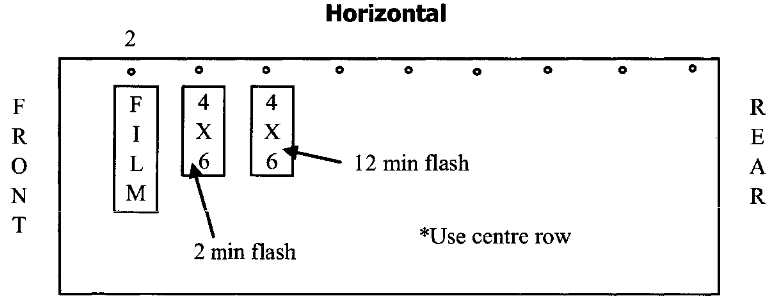
IR:
Convection:
Bypass Damper:
Middle Damper:
Upper Damper:
Lower Damper:
Main Supply Damper:

Panel Oven Settings:

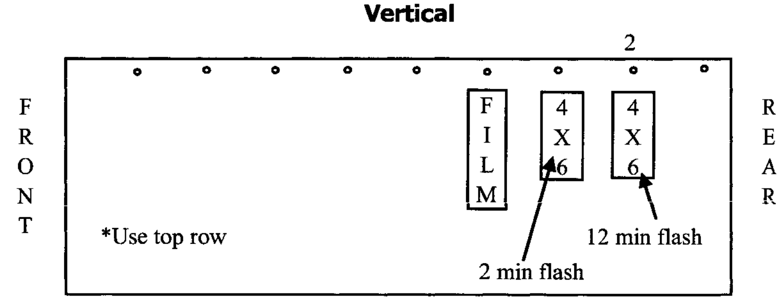
Ambiant Flash Time:	2 min & 12 min
Normal Cure Temperature:	291
Normal Cure Time:	25 min

Panel Locations:

Horizontal

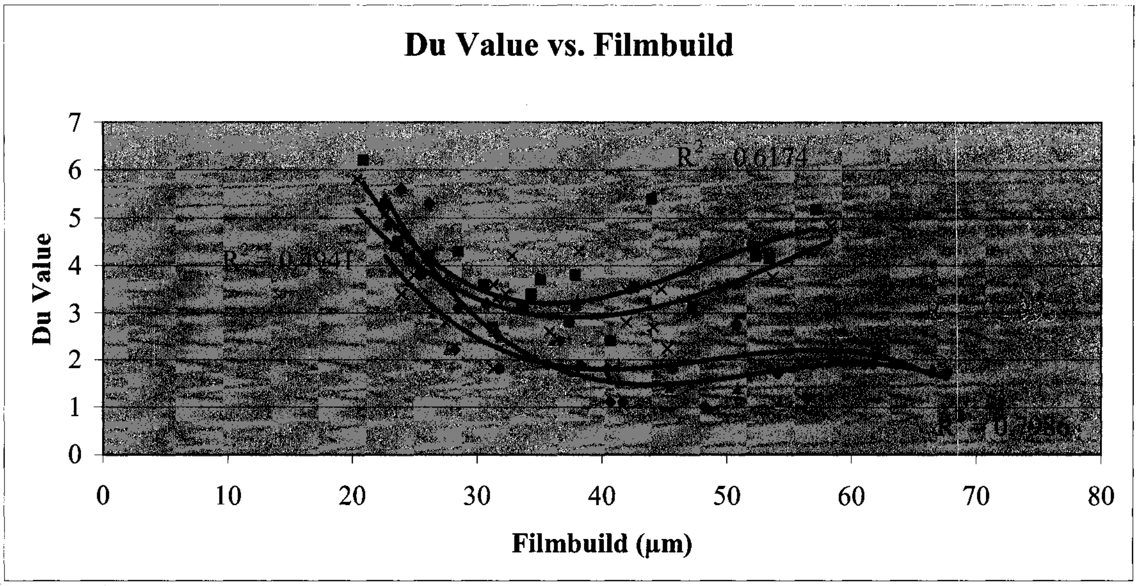


Vertical



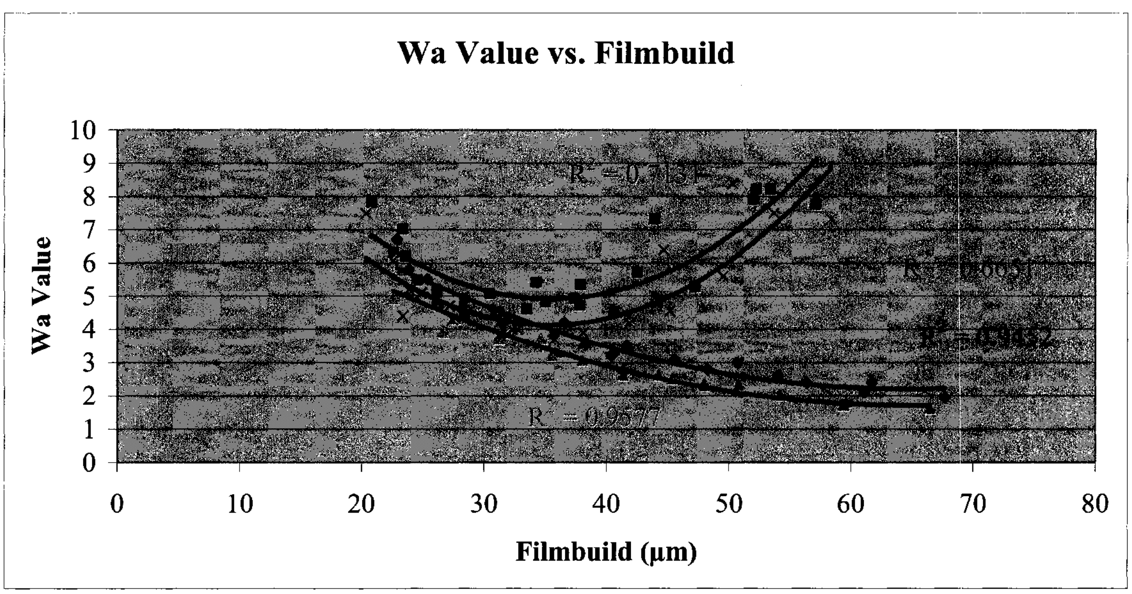
Notes:

APPENDIX C – RESULTS: CLEARCOAT FILM THICKNESS STUDY

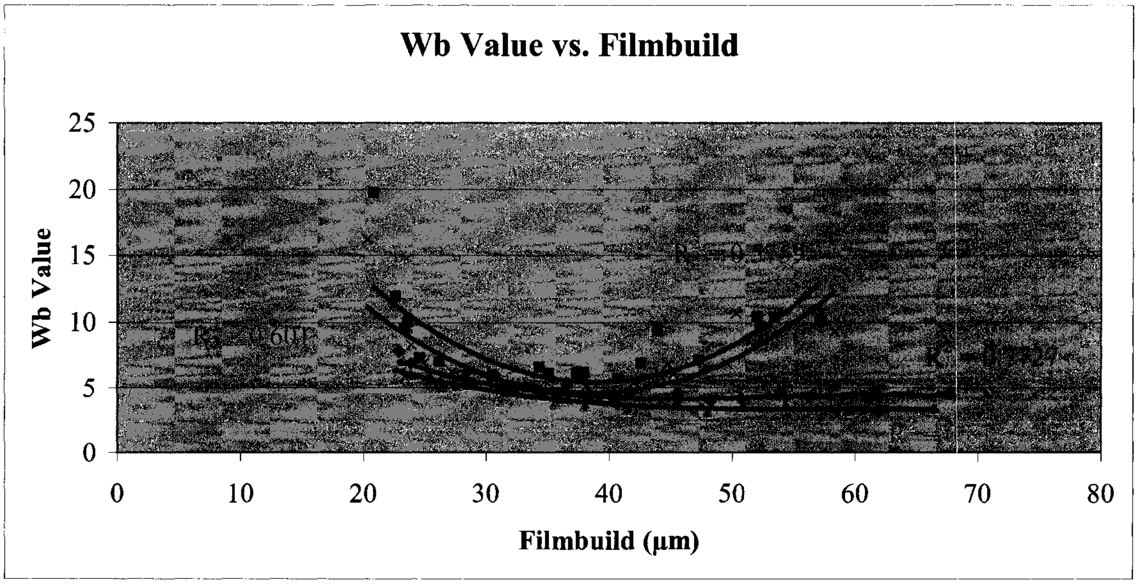


R^2<0.64 - Du not affected by clearcoat thickness

◆ 2 Min. Horz ■ 2 Min. Vert ▲ 12 Min. Horz × 12 Min. Vert

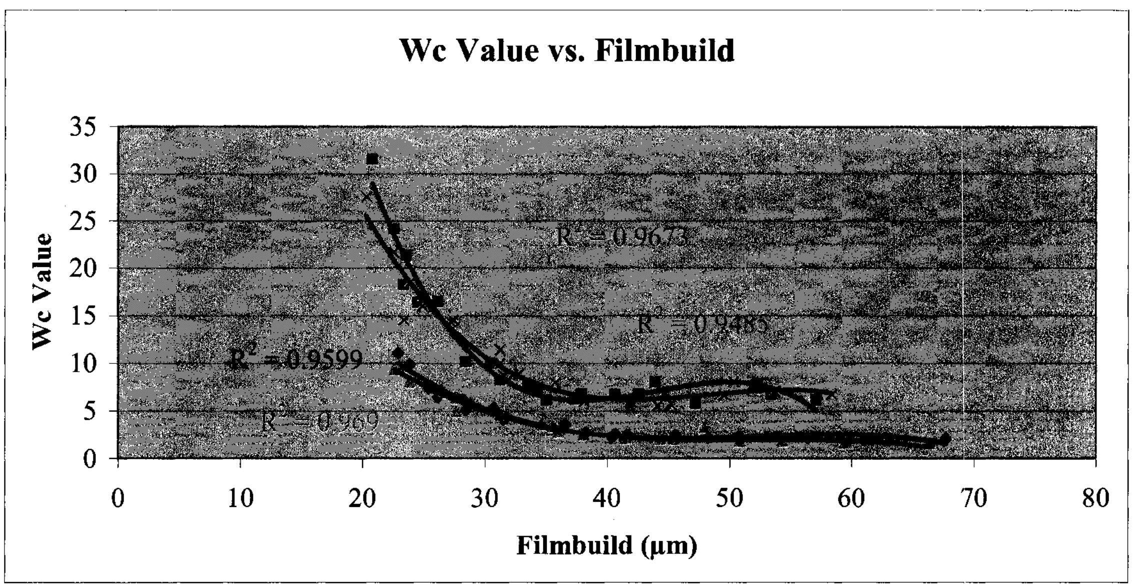


R^2>0.64, Wa is affected by clearcoat thickness - horizontal breakpoint = >67.8 µm, vertical breakpoint is between 26.2 µm and 41.9 µm

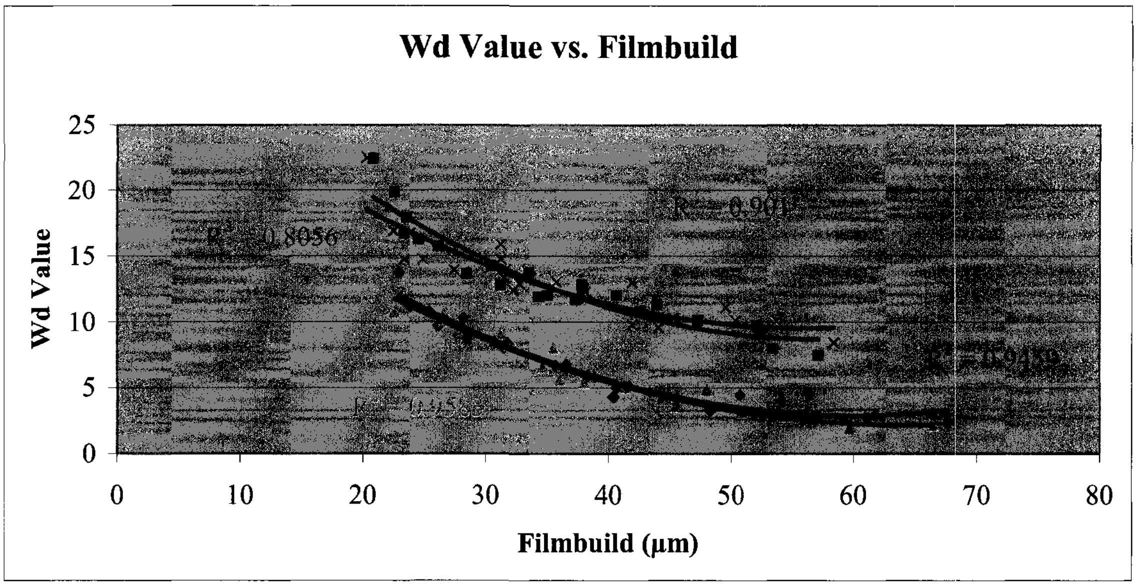


R^2>0.64, horizontal Wb affected by clearcoat thickness - breakpoint = 35 µm

◆ 2 Min. Horz ■ 2 Min. Vert ▲ 12 Min. Horz × 12 Min. Vert

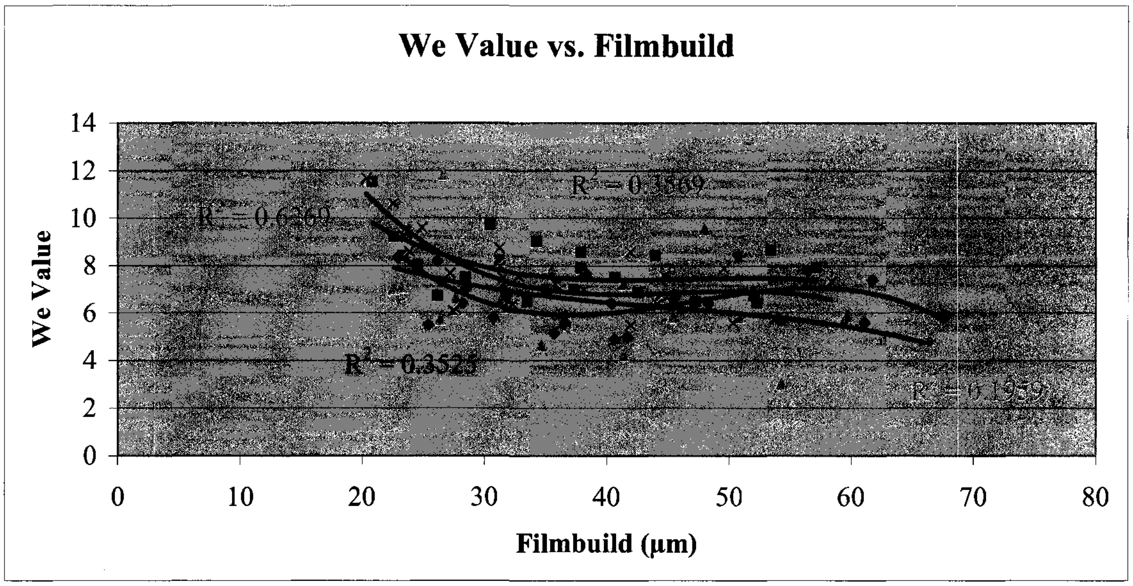


R^2>0.64, Wc is affected by clearcoat thickness - breakpoint = 38 µm



R^2>0.64, Wd is affected by clearcoat thickness - breakpoint = >55 µm

◆ 2 Min. Horz ■ 2 Min. Vert ▲ 12 Min. Horz × 12 Min. Vert



R^2<0.64, We is not affected by clearcoat thickness

APPENDIX D – SUBSTRATE PROFILOMETER AND ELCOMETER MEASUREMENTS

Profilometer Readings

Panel 1 - 12 x 18 Aluminum

7	9	8	6
6	8	5	6
5	7	5	8
6	6	6	5
7	7	6	7
6	6	6	7
7	6	6	5
7	5	7	7
7	6	7	7

AVG = 6.444444 SD = 0.969372

Panel 2 - 12 x 18 Aluminum

6	7	6	10
7	9	8	8
7	6	6	5
8	5	5	7
6	6	7	6
7	8	6	7
6	6	6	7
9	6	7	9
7	6	9	12

AVG = 7.027778 SD = 1.502115

Panel 3 - 12 x 18 Aluminum

7	6	5	14
8	6	6	5
9	7	6	6
7	6	8	6
7	6	6	6
6	7	6	7
7	7	8	6
8	8	7	7
6	8	7	12

AVG = 7.055556 SD = 1.739367

Average SD = 1.40361798

Panel 1 - 10 x 10 PPG E-coat

10	9	8
8	8	8
7	9	9
7	9	10
9	8	9

AVG = 8.533333
SD = 0.915475

Panel 2 - 10 x 10 PPG E-coat

8	6	8
11	8	9
8	10	9
9	8	8
9	8	8

AVG = 8.466667
SD = 1.125463

Panel 3 - 10 x 10 PPG E-coat

9	8	9
9	8	9
8	8	9
9	8	9
9	8	9

AVG = 8.6
SD = 0.507093

Panel 4 - 10 x 10 PPG E-coat

8	7	8
8	8	9
10	7	8
8	11	10
10	7	8

AVG = 8.466667
SD = 1.245946

Average SD = 0.948494161

Panel 1 - PPG Primed

4
5
6
3
3
9

AVG = 5.2
SD = 2.48998

Panel 2 - PPG Primed

3
5
4
4
5
3

AVG = 4.2
SD = 0.83666

Panel 3 - PPG Primed

5
4
4
3
2
4

AVG = 3.4
SD = 0.894427

Panel 4 - PPG Primed

5
4
4
4
6
3

AVG = 4.2
SD = 1.095445

Average SD = 1.329128063

Elcometer Readings

Panel 1 - 12 x 18 Aluminum

0.13	0.155	0.155	0.115	0.115	0.13	0.115	0.095	0.115	0.13	0.095	0.115	0.13	0.095	0.075	0.115	0.095	0.095
0.13	0.115	0.13	0.13	0.115	0.13	0.115	0.075	0.115	0.095	0.115	0.115	0.095	0.115	0.115	0.115	0.075	0.095
0.13	0.13	0.155	0.13	0.115	0.115	0.115	0.13	0.13	0.115	0.115	0.115	0.095	0.115	0.095	0.075	0.095	0.075
0.155	0.155	0.095	0.095	0.115	0.13	0.115	0.115	0.115	0.115	0.155	0.13	0.115	0.095	0.075	0.095	0.095	0.075
0.155	0.13	0.13	0.155	0.115	0.115	0.115	0.115	0.095	0.115	0.155	0.095	0.095	0.115	0.115	0.095	0.115	0.075
0.155	0.155	0.13	0.13	0.115	0.13	0.095	0.115	0.155	0.115	0.155	0.075	0.095	0.115	0.075	0.095	0.075	0.095
0.115	0.13	0.155	0.115	0.13	0.115	0.115	0.155	0.115	0.115	0.155	0.115	0.095	0.095	0.095	0.115	0.075	0.075
0.115	0.155	0.115	0.115	0.115	0.115	0.115	0.115	0.095	0.075	0.115	0.115	0.095	0.095	0.095	0.115	0.095	0.075
0.115	0.155	0.115	0.115	0.13	0.115	0.115	0.115	0.115	0.115	0.13	0.095	0.115	0.095	0.115	0.095	0.115	0.075
0.115	0.13	0.115	0.115	0.13	0.095	0.115	0.115	0.075	0.095	0.115	0.095	0.115	0.095	0.115	0.095	0.095	0.075
0.13	0.115	0.115	0.115	0.155	0.115	0.115	0.095	0.075	0.115	0.155	0.115	0.075	0.115	0.075	0.095	0.095	0.095
0.095	0.115	0.075	0.075	0.115	0.115	0.095	0.095	0.115	0.115	0.13	0.095	0.095	0.155	0.095	0.115	0.075	0.075

AVG = 0.111481 SD = 0.021309

Panel 2 - 12 x 18 Aluminum

0.075	0.06	0.06	0.075	0.075	0.075	0.06	0.075	0.095	0.095	0.075	0.075	0.075	0.115	0.06	0.075	0.075	0.06
0.06	0.075	0.075	0.06	0.075	0.06	0.075	0.075	0.075	0.075	0.075	0.06	0.06	0.075	0.075	0.06	0.06	0.06
0.075	0.075	0.075	0.095	0.075	0.075	0.075	0.075	0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.06	0.06	0.06
0.075	0.075	0.075	0.075	0.115	0.075	0.075	0.06	0.095	0.075	0.095	0.075	0.06	0.075	0.06	0.075	0.075	0.06
0.075	0.075	0.095	0.115	0.075	0.075	0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
0.075	0.075	0.06	0.095	0.075	0.075	0.075	0.075	0.075	0.095	0.075	0.075	0.075	0.06	0.075	0.06	0.075	0.075
0.095	0.075	0.075	0.075	0.075	0.075	0.095	0.075	0.095	0.095	0.075	0.075	0.075	0.06	0.06	0.095	0.035	0.075
0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.095	0.075	0.075	0.075	0.06	0.075	0.075	0.06	0.075
0.075	0.075	0.075	0.075	0.075	0.075	0.06	0.075	0.075	0.075	0.06	0.095	0.095	0.06	0.115	0.095	0.095	0.075
0.075	0.06	0.06	0.075	0.075	0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.095	0.075	0.075	0.115	0.06
0.06	0.075	0.06	0.075	0.06	0.075	0.06	0.075	0.06	0.06	0.075	0.075	0.06	0.075	0.075	0.075	0.075	0.06
0.075	0.06	0.075	0.075	0.095	0.095	0.075	0.075	0.06	0.075	0.075	0.075	0.095	0.06	0.075	0.075	0.075	0.075

AVG = 0.075 SD = 0.011714

Panel 3 - 12 x 18 Aluminum

0.115	0.115	0.095	0.075	0.075	0.075	0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
0.115	0.115	0.095	0.115	0.075	0.075	0.075	0.095	0.095	0.075	0.075	0.075	0.075	0.075	0.06	0.06	0.06	0.075
0.095	0.075	0.095	0.115	0.095	0.115	0.075	0.075	0.095	0.095	0.095	0.06	0.035	0.06	0.13	0.075	0.06	0.035
0.075	0.095	0.075	0.095	0.075	0.075	0.115	0.075	0.075	0.115	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.06
0.075	0.095	0.075	0.115	0.075	0.075	0.075	0.095	0.075	0.06	0.095	0.115	0.075	0.075	0.075	0.075	0.06	0.075
0.06	0.095	0.075	0.075	0.075	0.035	0.06	0.115	0.06	0.075	0.095	0.075	0.075	0.075	0.095	0.095	0.06	0.06
0.13	0.115	0.075	0.06	0.075	0.075	0.075	0.075	0.06	0.075	0.075	0.075	0.075	0.075	0.035	0.075	0.075	0.075
0.095	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.035	0.075	0.075	0.06	0.075	0.06	0.06
0.115	0.095	0.095	0.075	0.095	0.075	0.075	0.075	0.06	0.095	0.095	0.06	0.06	0.075	0.06	0.075	0.06	0.075
0.115	0.035	0.115	0.095	0.075	0.115	0.075	0.075	0.13	0.075	0.095	0.095	0.075	0.075	0.06	0.06	0.075	0.06
0.075	0.075	0.095	0.115	0.075	0.115	0.075	0.075	0.075	0.115	0.115	0.095	0.075	0.075	0.075	0.075	0.075	0.075
0.115	0.095	0.115	0.095	0.095	0.095	0.075	0.075	0.095	0.095	0.095	0.075	0.095	0.075	0.075	0.075	0.075	0.075

AVG = 0.111481 SD = 0.021309

Average SD = 0.054332

Panel 1 - 10 x 10 PPG E-coat

1.07	1.085	1.045
1.065	1.07	1.03
1.065	1.08	1.07

AVG = 1.064444
SD = 0.017038

Panel 2 - 10 x 10 PPG E-coat

1.01	1.045	1.045
0.99	1.08	1.045
1.04	1.04	1.045

AVG = 1.037778
SD = 0.025139

Panel 3 - 10 x 10 PPG E-coat

1.14	1.045	1.01
1.075	1.055	1.025
1.065	1.075	1.075

AVG = 1.062778
SD = 0.03709

Panel 4 - 10 x 10 PPG E-coat

1.09	1.07	1.01
1.11	1.085	1.03
1.075	1.075	0.995

AVG = 1.06
SD = 0.039051

Average SD = 0.029579

Panel 1 - PPG Primed

2.35
2.3
2.23
2.155
2.305
2.38
2.37
2.47
2.47
2.195
2.19
2.14

AVG = 2.293
SD = 0.163003

Panel 2 - PPG Primed

2.345
2.295
2.12
2.185
2.32
2.345
2.415
2.45
2.415
2.31
2.265
2.195

AVG = 2.327
SD = 0.105392

Panel 3 - PPG Primed

2.35
2.47
2.25
2.245
2.4
2.4
2.59
2.59
2.46
2.29
2.285
2.22

AVG = 2.369
SD = 0.152168

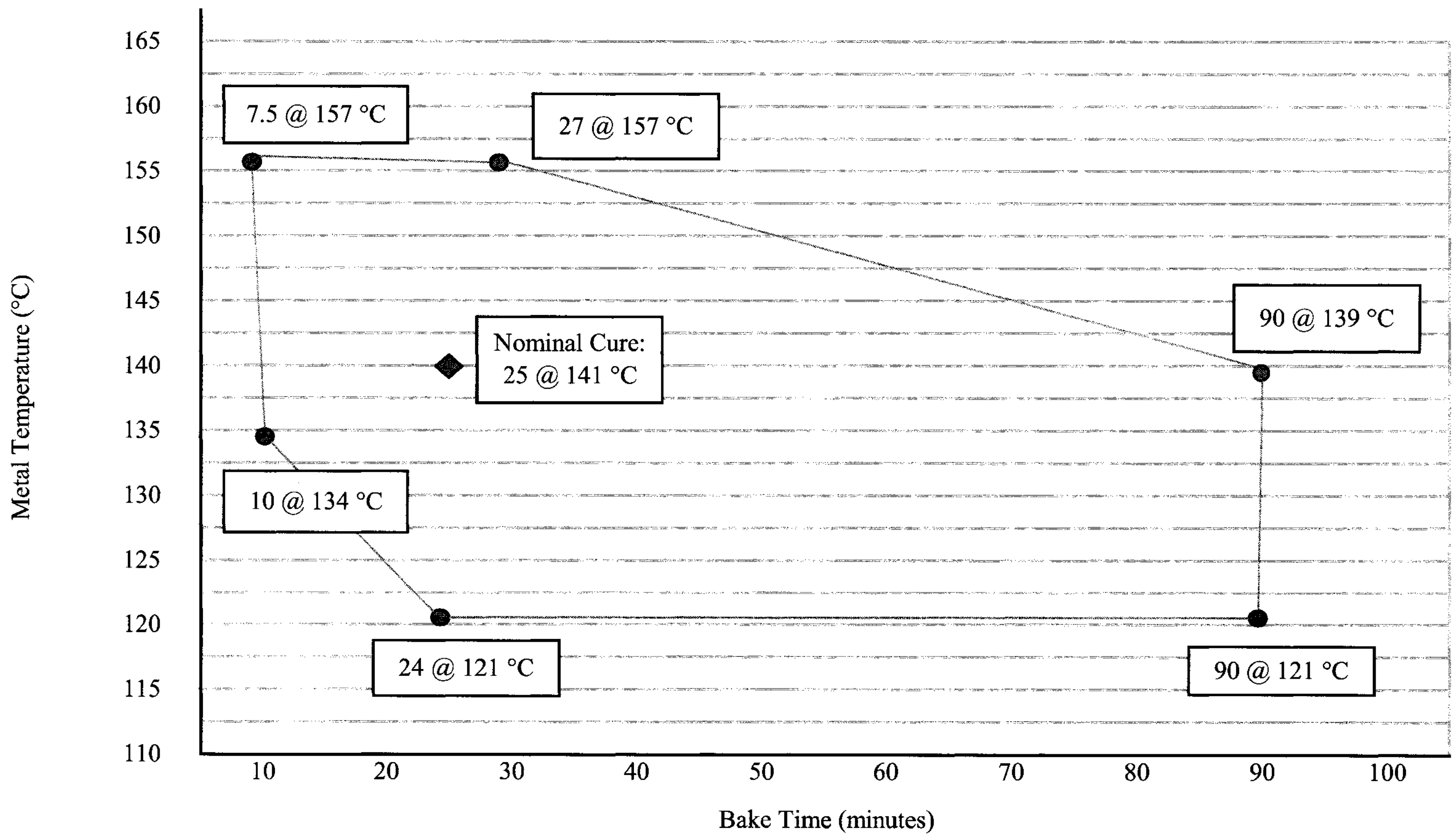
Panel 4 - PPG Primed

2.63
2.53
2.4
2.305
2.51
2.585
2.62
2.75
2.615
2.475
2.5
2.46

AVG = 2.56
SD = 0.122423

Average SD = 0.135747

APPENDIX E – DUPONT RK-8064 CURE WINDOW


Metal Temperature (°C)
165
160
155
150
145
140
135
130
125
120
115
110
7.5 @ 157 °C
27 @ 157 °C
90 @ 139 °C
Nominal Cure:
25 @ 141 °C
10 @ 134 °C
24 @ 121 °C
90 @ 121 °C
10
20
30
40
50
60
70
80
90
100
Bake Time (minutes)

APPENDIX F – DOE SUMMARY MATRICES

Run #	DOE	Dehydration Solids	Booth Humidity/Temp	Recip Flow Rate cm^3/min	Recip Fan Air L/min	Bell Flow Rate cm3/min
2	Target 1	185F	63%RH/73F	350	300	280/235
4	Target 2	185F	63%RH/73F	350	300	280/235
5	24	180F	68%RH/68F	420	360	250/210
6	7	180F	68%RH/68F	280	360	310/260
7	8	180F	68%RH/68F	280	360	310/260
8	6	180F	68%RH/68F	420	360	250/210
9	18	180F	68%RH/68F	280	360	310/260
10	21	180F	68%RH/68F	420	360	250/210
12	10	180F	58%RH/78F	280	240	310/260
13	19	180F	58%RH/78F	420	240	250/210
14	1	180F	58%RH/78F	420	240	250/210
15	12	180F	58%RH/78F	280	240	310/260
16	14	180F	58%RH/78F	280	240	310/260
17	5	180F	58%RH/78F	420	240	250/210
20	17	190F	68%RH/68F	420	240	310/260
21	22	190F	68%RH/68F	420	240	310/260
22	20	190F	68%RH/68F	420	240	310/260
23	11	190F	58%RH/78F	280	360	250/210
24	4	190F	58%RH/78F	420	360	310/260
25	16	190F	58%RH/78F	420	360	310/260
26	9	190F	58%RH/78F	280	360	250/210
27	2	190F	58%RH/78F	420	360	310/260
28	15	190F	58%RH/78F	280	360	250/210
29	3	190F	68%RH/68F	280	240	250/210
30	23	190F	68%RH/68F	280	240	250/210
31	13	190F	68%RH/68F	280	240	250/210
32	Target 3	185F	63%RH/73F	350	300	280/235
33	Target 4	185F	63%RH/73F	350	300	280/235
34	Target 5	185F	63%RH/73F	350	300	280/235

Run Order	Dehydration Solids	Booth Humidity/Temp	Recip Flow Rate cm^3/min	Recip Fan Air L/min	Bell Flow Rate cm^3/min
1	80%	58%RH/78F	20%	-15%	-10%
2	90%	58%RH/78F	20%	15%	10%
3	90%	68%RH/68F	-20%	-15%	-10%
4	90%	58%RH/78F	20%	15%	10%
5	80%	58%RH/78F	20%	-15%	-10%
6	80%	68%RH/68F	20%	15%	-10%
7	80%	68%RH/68F	-20%	15%	10%
8	80%	68%RH/68F	-20%	15%	10%
9	90%	58%RH/78F	-20%	15%	-10%
10	80%	58%RH/78F	-20%	-15%	10%
11	90%	58%RH/78F	-20%	15%	-10%
12	80%	58%RH/78F	-20%	-15%	10%
13	90%	68%RH/68F	-20%	-15%	-10%
14	80%	58%RH/78F	-20%	-15%	10%
15	90%	58%RH/78F	-20%	15%	-10%
16	90%	58%RH/78F	20%	15%	10%
17	90%	68%RH/68F	20%	-15%	10%
18	80%	68%RH/68F	-20%	15%	10%
19	80%	58%RH/78F	20%	-15%	-10%
20	90%	68%RH/68F	20%	-15%	10%
21	80%	68%RH/68F	20%	15%	-10%
22	90%	68%RH/68F	20%	-15%	10%
23	90%	68%RH/68F	-20%	-15%	-10%
24	80%	68%RH/68F	20%	15%	-10%

APPENDIX G – MATERIAL TESTING RESULTS

Basecoat – DuPont Silver Steel (DA4)

Sample	ACRF - Dupont DA4 BC# 1
Sampled	Sampled on October 31 / 2005 @ 8:30 am
Test Date	October 31 / 2005
Lab#	122253

#4 Ford Cup Viscosity (Sample as Received)

Ref	36.04 seconds
	35.81 seconds
	36.03 seconds
	35.90 seconds
Ave	**35.91** seconds

Solids Concentration

Tray (g) =	0.9368
Sample (g) =	0.7681
Solids + Tray (g) =	1.1112
Solids (g) =	0.1744
Solids Concentration =	**22.7%**

Brookfield Viscosity **DV II+**

Spindle	RPM	Viscosity - CP	Torque %
3	200	240.0	48.0
4	200	250.0	25.0

Density

264.13	
167.73	
9.66	lb/Imperial gallon
8.04	lb/US gallon

All samples were tested after 15 minutes shake.

Tests Performed By *Leonello Duronio*

Clearcoat – DuPont Super High Solids (RK-8064)

Sample	ACRF - Dupont RK-8064 C Horizontal
Sampled	Sampled on October 31 / 2005 @ 8:30 am
Test Date	November 3 / 2005
Lab#	122255

#4 Ford Cup Viscosity (Sample as Received)

Ref	52.60 seconds
	53.46 seconds
	53.35 seconds
	53.40 seconds
Ave	**53.40** seconds

Solids Concentration

Tray (g) =	0.9356
Sample (g) =	0.7831
Solids + Tray (g) =	1.3948
Solids (g) =	0.4592
Solids Concentration =	**58.6%**

Brookfield Viscosity **DV II+**

Spindle	RPM	Viscosity - CP	Torque %
3	200	232.5	46.5
4	200	216.0	21.6

Density

259.32	
167.73	
9.18	lb/Imperial gallon
7.64	lb/US gallon

All samples were tested after 15 minutes shake.

Tests Performed By *Leonello Duronio*

APPENDIX H – PROJECT SETUP PARAMETERS: DOE PANELS

Project 42 - Wavescan Masters (DuPont)

C1 - Basecoat Bells		C1 - Basecoat Robots		C3 - Clearcoat Bells	
Silver Steel- DA4		**Silver Steel - DA4**		**Gen IV ES W - RK 8064**	
Supply Pressure:	135	**Supply Pressure:**	100	**Supply Pressure:**	100
Return Pressure:	70	**Return Pressure:**	N/A	**Return Pressure:**	N/A
Flow:	2.9	**Flow:**	N/A	**Flow:**	N/A
Pump Speed:	75	**Pump Speed:**	N/A	**Pump Speed:**	N/A
Agitation:	On	**Agitation:**	On	**Agitation:**	Off
Temperature:	75 - 85 ± 2 F	**Temperature:**	75 - 85 ± 2 F	**Temperature:**	90 ± 2 F
Viscosity Specification:	0.2 ± 0.1 poise	**Viscosity Specification:**	0.2 ± 0.1 poise	**Viscosity Specification:**	47.5 ± 2.5 s
Filter Size:	150 micron	**Filter Size:**	150 micron	**Filter Size:**	None
BC Bell Zone Settings		**BC Robot Zone Settings**		**CC Bell Zone Settings**	
Temperature:	80 ± 5 F	**Temperature:**	80 ± 5 F	**Temperature:**	75 ± 5 F
Humidity:	65 ± 5 %	**Humidity:**	65 ± 5 %	**Humidity:**	60%
Downdraft:	60 ± 10 fpm	**Downdraft:**	80 ± 10 fpm	**Downdraft:**	60 ± 10 fpm
Filmbuild Specification:	0.5 mils	**Filmbuild Specification:**	0.2 mils	**Filmbuild Specification:**	1.8 - 2.2 mils

Project 42 - Wavescan Masters (DuPont)

C1 - Basecoat Bells

BC Bell Program Settings

Style:	28
Colour:	1
Option:	1
Line Speed:	16 fpm
# Passes:	1

Control Run BC Bell Brush Files

Vertical -	Flow Rate:	280
	Shaping Air:	280
	High Voltage:	70
	Bell Speed:	450
Horizontal -	Flow Rate:	235
	Shaping Air:	305
	High Voltage:	70
	Bell Speed:	450

BC Bell Contour Program

Vertical Bell - Vertical:	119
Horizontal:	156
Normalization:	0
Horizontal Bell - Vertical:	223
Oscillation:	4
Normalization:	0
Indexing:	45

C1 - Basecoat Robots

BC Robot Program Settings

Style:	28
Colour:	1
Option:	1
Line Speed:	16 fpm
# Passes:	1

Control Run BC Robot Brush Files

Flow Rate:	350
Fan Air:	300
Atomizing Air:	350
Tip Speed:	v1200
Restrictor Size:	1.0 mm

BC Program - Robots Only

Robot:	1
Program Style:	28
With Conveyor:	Yes
Option Number:	1

C3 - Clearcoat Bells

CC Bell Program Settings

Style:	28
Colour:	3
Option:	1
Line Speed:	16 fpm
# Passes:	2

Control Run CC Bell Brush Files

Vertical -	Flow Rate:	225
	Shaping Air:	175
	High Voltage:	90
	Bell Speed:	400
Horizontal -	Flow Rate:	245
	Shaping Air:	195
	High Voltage:	90
	Bell Speed:	400

CC Bell Contour Program

Vertical Bell - Vertical:	118
Horizontal:	156
Normalization:	0
Horizontal Bell - Vertical:	229
Oscillation:	4
Normalization:	0
Indexing:	43

Note: Bell 1-3 is used to spray the vertical panels, Bell 3-2 is used to spray the horizontals.

Project 42 - Wavescan Masters (DuPont)

Conveyor Settings:

Zone	Line Speed (fpm)	Flash Time (min)	Delay Timers (s)
B/C Manual	16.4		-
B/C Bell	12	0:47 H 1:36 V	3
B/C Robot	16.4	3:36H 3:24 V	3
B/C Vestibule	16.4		3
Electric IR	7		3
Convection	7	3:06	3
C/C Vestibule	22	4:46 H	75
C/C Bell	16.4	4:25 V	3
C/C Reverse	59	4:55 H	3
C/C Manual	59	4:58 V	40

Note: Use e-coated filmbuild panels and steel solids panels
The second 10x10 is coated with clearcoat only. Foil until after dehyd.

Dehydration Oven Settings:

Temperature: 180F, 185F, 190F
Solids: 70-92%

IR: Off
Convection: 180F, 185F, 190F
Bypass Damper: 6HFC, 2HFC
Middle Damper: 2.5HFC, 6HFC
Upper Damper: 4HFC, 1HFC
Lower Damper: 10-12" Open
Main Supply Damper: Open

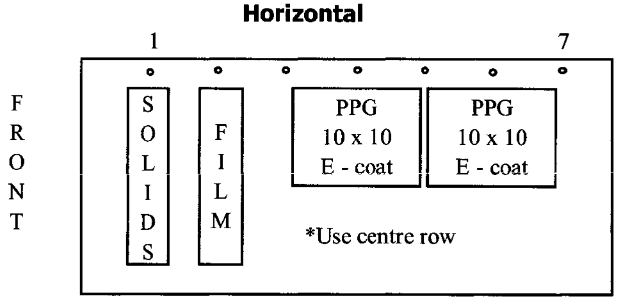
Panel Oven Settings:

Ambiant Flash Time: 10 min
Temperature: 200/291
Time: 32 min

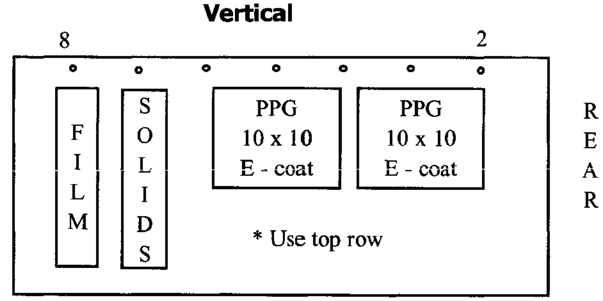
Note: Place panels into oven set at 200 F.
As soon as panels are in oven, increase temperature to 291 F.
Remove panels after 32 min.

Panel Locations:

Horizontal

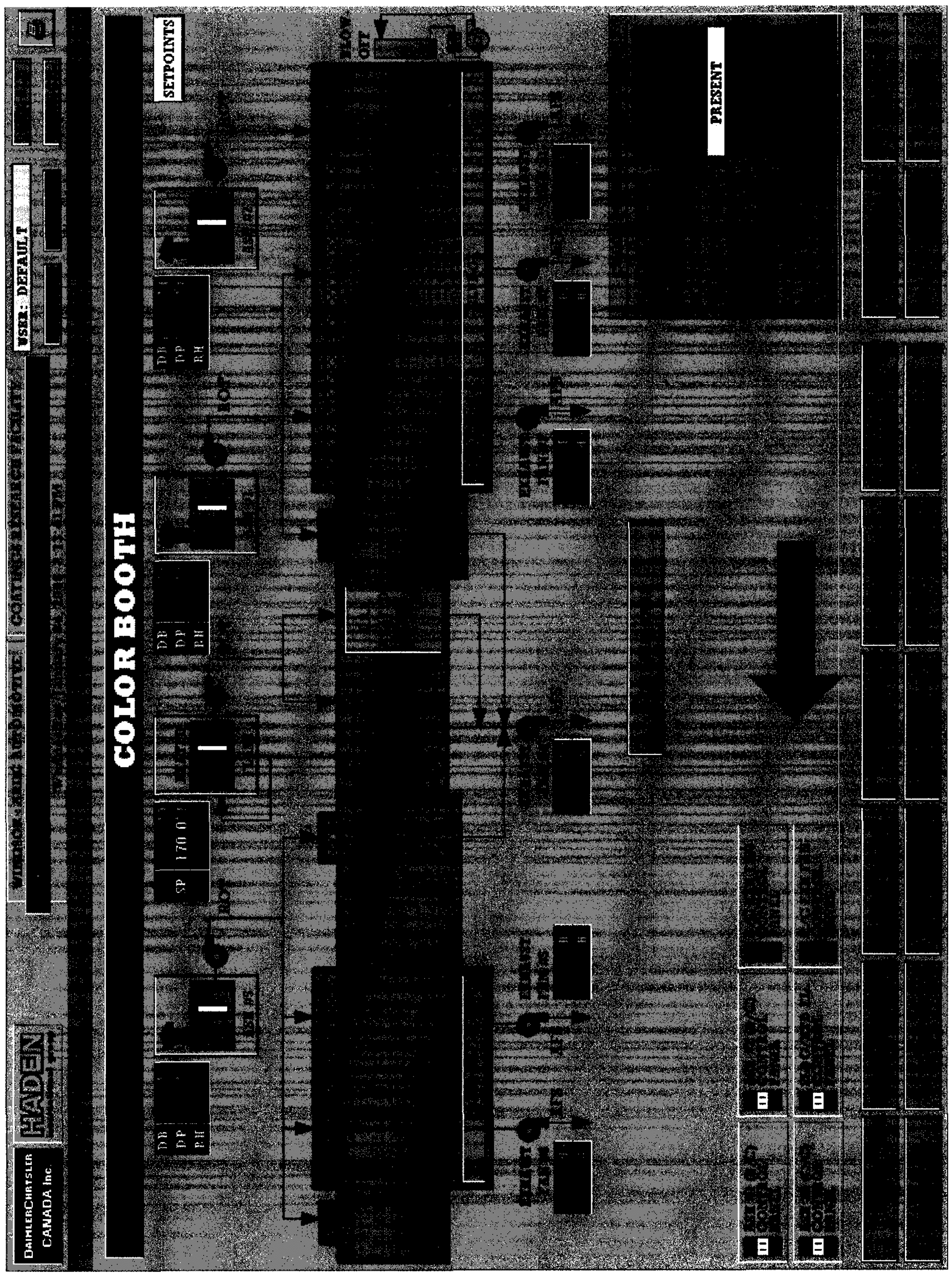


Vertical



Note: Use 85/15 IPA/DI solvent wipes and BS20CB tack rags to prepare panels

APPENDIX I – EXAMPLE ENVIRONMENTAL BOOTH CONDITIONS


DAIMLERCHRYSLER
CANADA Inc.
HADEN
USER: DEFAULT
COLOR BOOTH
SETPOINTS
BLOW OFF
PRESENT

APPENDIX J – APPEARANCE ELEMENT SUMMARY DATA

Target 1

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.7	13.8	29.3	14.2	14.0	10.6
Reading 2	6.7	12.4	26.5	13.2	13.1	4.7
Reading 3	5.6	10.4	23.6	10.7	10.9	7.0
Reading 4	4.6	10.0	22.3	11.2	12.3	7.1
Reading 5	6.0	10.4	21.6	11.6	13.1	8.5
Average	5.9	11.4	24.7	12.2	12.7	7.6
Cofficient of Variation	0.15	0.14	0.13	0.12	0.09	0.29

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.3	27.6	41.9	21.6	14.2	7.6
Reading 2	21.7	27.0	39.5	20.9	14.6	7.6
Reading 3	20.0	24.9	39.5	19.2	13.3	8.4
Reading 4	21.5	25.1	40.4	20.4	11.4	12.7
Reading 5	20.4	25.6	38.6	17.9	13.6	11.7
Average	21.2	26.0	40.0	20.0	13.4	9.6
Cofficient of Variation	0.04	0.05	0.03	0.07	0.09	0.25

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	10.5	25.2	17.3	17.7	13.1
Reading 2	5.8	10.3	22.3	16.8	18.7	10.4
Reading 3	5.3	9.9	23.6	16.3	18.6	6.5
Reading 4	5.9	10.8	23.9	15.1	16.4	6.4
Reading 5	6.6	9.7	22.3	15.7	15.8	6.1
Average	6.1	10.2	23.5	16.2	17.4	8.5
Cofficient of Variation	0.11	0.04	0.05	0.05	0.07	0.37

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.1	32.7	42.3	22.1	17.4	10.9
Reading 2	26.0	35.9	43.5	21.9	18.5	8.1
Reading 3	25.9	33.0	42.4	21.4	18.2	10.0
Reading 4	25.4	33.0	42.7	20.6	16.5	9.7
Reading 5	24.8	32.8	42.0	20.3	14.5	12.1
Average	25.4	33.5	42.6	21.3	17.0	10.2
Cofficient of Variation	0.02	0.04	0.01	0.04	0.09	0.15

Summary

H - CC	5.9	11.4	24.7	12.2	12.7	7.6
H - T	21.2	26.0	40.0	20.0	13.4	9.6
V - CC	6.1	10.2	23.5	16.2	17.4	8.5
V - T	25.4	33.5	42.6	21.3	17.0	10.2

Target 2

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	9.4	19.8	34.5	20.5	20.2	11.6
Reading 2	9.2	19.1	31.8	18.0	19.1	6.1
Reading 3	8.0	15.7	27.7	19.4	18.0	8.3
Reading 4	7.6	13.8	26.5	17.3	17.1	12.0
Reading 5	6.7	12.8	24.9	15.5	17.6	4.7
Average	8.2	16.2	29.1	18.1	18.4	8.5
Cofficient of Variation	0.14	0.19	0.14	0.11	0.07	0.38

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.2	32.2	44.5	21.1	15.1	12.1
Reading 2	24.6	30.4	40.8	19.6	16.6	9.6
Reading 3	25.0	29.6	37.1	19.6	15.7	8.6
Reading 4	25.4	30.6	39.9	21.3	17.9	9.6
Reading 5	24.2	28.9	37.3	19.1	14.9	10.1
Average	24.7	30.3	39.9	20.1	16.0	10.0
Cofficient of Variation	0.02	0.04	0.08	0.05	0.08	0.13

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	9.3	12.7	26.0	19.2	19.3	5.7
Reading 2	8.4	12.9	26.3	21.1	21.5	8.1
Reading 3	8.7	12.4	26.8	19.8	20.9	7.6
Reading 4	6.2	12.2	26.0	20.0	21.0	7.0
Reading 5	8.1	12.3	25.7	18.3	17.5	8.4
Average	8.1	12.5	26.2	19.7	20.0	7.4
Cofficient of Variation	0.14	0.02	0.02	0.05	0.08	0.15

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.0	30.3	39.0	21.0	16.3	7.1
Reading 2	23.7	30.2	42.5	21.2	13.8	11.4
Reading 3	25.1	30.7	40.4	20.8	18.3	6.0
Reading 4	23.7	39.6	40.7	21.2	15.6	9.2
Reading 5	23.5	30.7	41.4	21.1	15.7	11.4
Average	24.0	32.3	40.8	21.1	15.9	9.0
Cofficient of Variation	0.03	0.13	0.03	0.01	0.10	0.27

Summary

H - CC	8.2	16.2	29.1	18.1	18.4	8.5
H - T	24.7	30.3	39.9	20.1	16.0	10.0
V - CC	8.1	12.5	26.2	19.7	20.0	7.4
V - T	24.0	32.3	40.8	21.1	15.9	9.0

Target 3

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.5	14.0	27.4	17.2	15.6	6.8
Reading 2	6.1	11.5	22.2	12.4	13.8	6.8
Reading 3	5.8	8.3	18.7	10.7	13.1	6.5
Reading 4	3.8	8.3	19.9	9.6	10.4	7.9
Reading 5	4.5	7.3	17.7	9.9	10.1	6.9
Average	5.3	9.9	21.2	12.0	12.6	7.0
Cofficient of Variation	0.21	0.28	0.18	0.26	0.19	0.08

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.7	29.2	39.6	18.9	14.3	8.6
Reading 2	22.9	29.6	38.3	20.3	16.2	10.8
Reading 3	22.2	29.6	37.1	18.8	15.1	6.9
Reading 4	20.9	27.4	37.9	19.3	14.3	9.7
Reading 5	19.1	25.4	35.2	17.0	12.1	7.3
Average	21.4	28.2	37.6	18.9	14.4	8.7
Cofficient of Variation	0.07	0.06	0.04	0.06	0.10	0.19

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.4	12.1	26.1	22.2	20.2	12.4
Reading 2	9.0	11.4	23.9	24.9	22.2	8.3
Reading 3	7.6	10.8	23.2	21.9	22.9	6.2
Reading 4	7.0	10.4	22.2	21.6	23.0	4.7
Reading 5	6.3	10.7	22.3	21.3	20.0	5.2
Average	7.3	11.1	23.5	22.4	21.7	7.4
Cofficient of Variation	0.15	0.06	0.07	0.06	0.07	0.43

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.8	28.2	35.6	18.7	16.0	8.3
Reading 2	22.8	27.7	37.1	19.4	14.4	9.7
Reading 3	21.8	27.9	35.6	17.6	15.3	6.4
Reading 4	22.6	27.6	36.9	19.4	16.5	10.6
Reading 5	21.9	26.2	36.9	20.0	15.1	13.2
Average	22.2	27.5	36.4	19.0	15.5	9.6
Cofficient of Variation	0.02	0.03	0.02	0.05	0.05	0.26

Summary

H - CC	5.3	9.9	21.2	12.0	12.6	7.0
H - T	21.4	28.2	37.6	18.9	14.4	8.7
V - CC	7.3	11.1	23.5	22.4	21.7	7.4
V - T	22.2	27.5	36.4	19.0	15.5	9.6

Target 4

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	8.0	15.4	30.5	15.9	15.9	5.2
Reading 2	7.0	14.5	26.2	14.5	14.2	5.2
Reading 3	6.3	12.5	25.0	13.1	17.7	9.5
Reading 4	5.9	10.3	23.4	10.8	11.6	6.2
Reading 5	6.0	9.6	23.2	10.6	12.2	7.4
Average	6.6	12.5	25.7	13.0	14.3	6.7
Cofficient of Variation	0.13	0.20	0.12	0.18	0.18	0.27

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.9	28.2	42.2	19.0	14.7	11.5
Reading 2	24.5	30.0	38.6	19.5	17.6	12.3
Reading 3	24.1	30.6	38.8	19.8	17.1	11.2
Reading 4	24.4	30.5	39.1	20.9	16.4	10.8
Reading 5	22.4	29.2	38.2	19.3	15.0	8.8
Average	23.5	29.7	39.4	19.7	16.2	10.9
Cofficient of Variation	0.05	0.03	0.04	0.04	0.08	0.12

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.0	10.1	23.7	18.9	18.5	6.2
Reading 2	5.8	10.7	23.7	18.8	19.3	6.6
Reading 3	5.7	10.2	22.5	18.4	18.8	5.7
Reading 4	5.9	10.3	22.5	16.2	18.5	6.3
Reading 5	6.9	11.0	23.7	19.1	19.2	7.7
Average	6.1	10.5	23.2	18.3	18.9	6.5
Cofficient of Variation	0.08	0.04	0.03	0.07	0.02	0.11

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.0	30.2	37.8	19.9	16.7	4.4
Reading 2	25.1	31.9	38.2	20.8	17.9	9.6
Reading 3	24.9	31.1	38.8	20.8	19.7	5.1
Reading 4	23.4	30.5	41.1	19.1	15.1	8.4
Reading 5	23.2	32.6	39.9	20.7	17.9	10.2
Average	24.1	31.3	39.2	20.3	17.5	7.5
Cofficient of Variation	0.04	0.03	0.03	0.04	0.10	0.35

Summary

H - CC	6.6	12.5	25.7	13.0	14.3	6.7
H - T	23.5	29.7	39.4	19.7	16.2	10.9
V - CC	6.1	10.5	23.2	18.3	18.9	6.5
V - T	24.1	31.3	39.2	20.3	17.5	7.5

Target 5

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	11.6	23.5	13.0	18.0	8.5
Reading 2	5.9	9.6	21.5	11.1	13.0	10.2
Reading 3	4.8	9.2	20.2	10.5	11.9	6.6
Reading 4	5.9	8.7	21.2	11.1	12.9	6.3
Reading 5	6.0	8.9	21.2	11.6	13.2	8.3
Average	5.9	9.6	21.5	11.5	13.8	8.0
Cofficient of Variation	0.13	0.12	0.06	0.08	0.17	0.20

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.7	25.8	38.4	19.3	14.5	11.4
Reading 2	21.4	24.2	36.9	18.4	14.0	14.9
Reading 3	20.2	26.0	37.2	17.4	14.8	9.4
Reading 4	18.8	21.5	35.8	16.2	11.1	9.9
Reading 5	18.4	20.3	36.6	17.1	9.8	8.9
Average	20.1	23.6	37.0	17.7	12.8	10.9
Cofficient of Variation	0.07	0.11	0.03	0.07	0.18	0.22

Vertical - Clearcoat Only

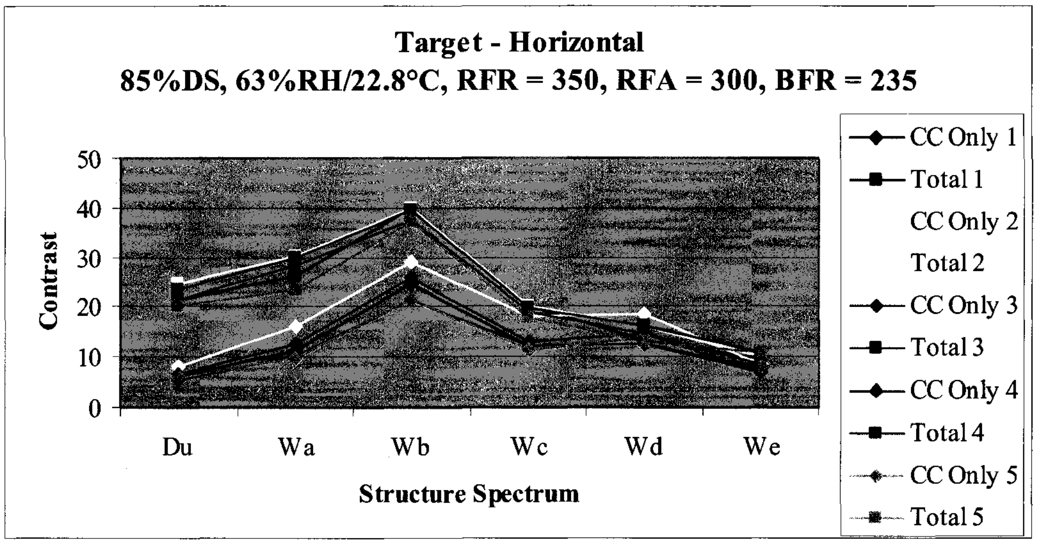
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.1	9.4	20.3	18.3	19.6	8.7
Reading 2	7.0	10.2	22.2	20.3	20.4	6.5
Reading 3	6.7	10.7	21.0	18.1	19.8	7.1
Reading 4	7.6	10.0	21.5	20.3	20.4	7.2
Reading 5	5.5	10.1	20.0	18.9	18.6	5.6
Average	6.6	10.1	21.0	19.2	19.8	7.0
Cofficient of Variation	0.12	0.05	0.04	0.06	0.04	0.16

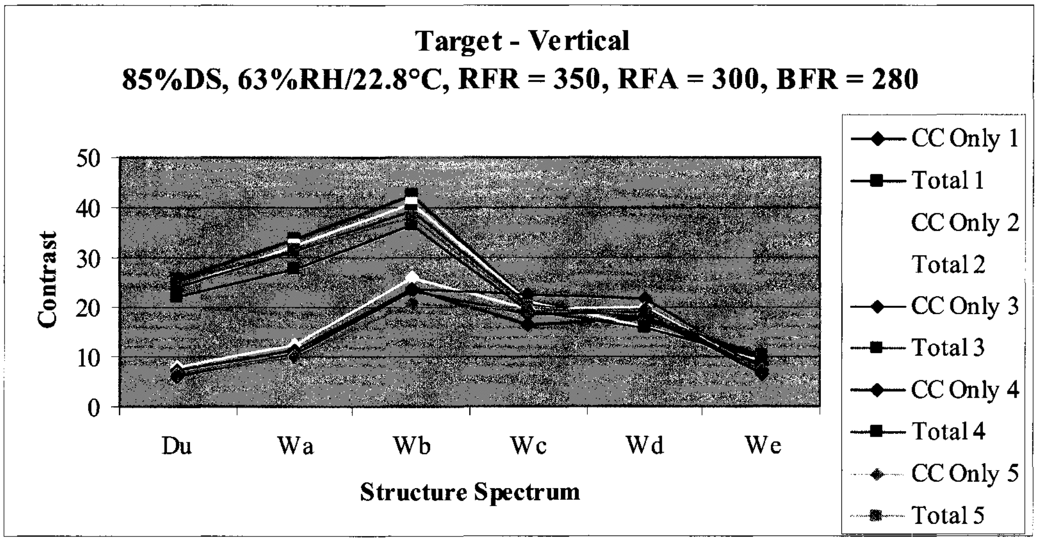
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.9	32.6	40.0	19.4	15.9	12.7
Reading 2	25.4	32.0	36.7	19.8	18.7	9.5
Reading 3	25.4	31.1	37.6	20.0	18.5	8.4
Reading 4	25.4	31.3	37.6	20.9	18.8	11.0
Reading 5	24.8	32.0	38.0	19.9	18.0	11.0
Average	25.4	31.8	38.0	20.0	18.0	10.5
Cofficient of Variation	0.02	0.02	0.03	0.03	0.07	0.16

Summary

H - CC	5.9	9.6	21.5	11.5	13.8	8.0
H - T	20.1	23.6	37.0	17.7	12.8	10.9
V - CC	6.6	10.1	21.0	19.2	19.8	7.0
V - T	25.4	31.8	38.0	20.0	18.0	10.5


Target - Horizontal
85%DS, 63%RH/22.8°C, RFR = 350, RFA = 300, BFR = 235
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only 1
Total 1
CC Only 2
Total 2
CC Only 3
Total 3
CC Only 4
Total 4
CC Only 5
Total 5


Target - Vertical
85%DS, 63%RH/22.8°C, RFR = 350, RFA = 300, BFR = 280
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only 1
Total 1
CC Only 2
Total 2
CC Only 3
Total 3
CC Only 4
Total 4
CC Only 5
Total 5

DOE 1

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	11.0	24.4	12.5	12.3	7.8
Reading 2	4.6	9.1	22.0	11.3	12.9	6.1
Reading 3	5.6	7.9	19.3	10.4	9.8	3.2
Reading 4	5.7	8.2	20.0	11.6	14.3	9.0
Reading 5	5.5	7.9	18.3	10.5	14.1	7.3
Average	5.6	8.8	20.8	11.3	12.7	6.7
Cofficient of Variation	0.13	0.15	0.12	0.08	0.14	0.33

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.4	30.0	43.9	22.6	13.7	9.4
Reading 2	21.8	21.8	41.2	23.3	16.3	7.9
Reading 3	20.6	26.0	40.9	23.5	14.4	11.5
Reading 4	18.5	23.2	38.0	22.0	13.8	9.0
Reading 5	19.3	21.3	39.1	21.6	13.4	11.6
Average	20.5	24.5	40.6	22.6	14.3	9.9
Cofficient of Variation	0.08	0.15	0.06	0.04	0.08	0.16

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.2	12.2	27.1	18.9	17.6	8.1
Reading 2	6.4	11.3	25.0	17.9	20.0	10.3
Reading 3	8.0	11.4	24.8	17.1	18.5	9.7
Reading 4	8.0	10.6	23.8	16.4	16.6	7.5
Reading 5	5.0	10.2	23.4	15.8	13.7	6.9
Average	6.9	11.1	24.8	17.2	17.3	8.5
Cofficient of Variation	0.18	0.07	0.06	0.07	0.14	0.17

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.3	34.0	42.3	21.5	18.4	11.2
Reading 2	26.9	35.7	41.8	22.3	17.6	7.1
Reading 3	27.1	36.1	42.0	21.1	18.8	10.5
Reading 4	26.5	35.6	44.4	21.8	18.3	12.7
Reading 5	25.6	35.0	44.9	21.4	14.7	7.2
Average	26.3	35.3	43.1	21.6	17.6	9.7
Cofficient of Variation	0.03	0.02	0.03	0.02	0.09	0.26

Summary

H - CC	5.6	8.8	20.8	11.3	12.7	6.7
H - T	20.5	24.5	40.6	22.6	14.3	9.9
V - CC	6.9	11.1	24.8	17.2	17.3	8.5
V - T	26.3	35.3	43.1	21.6	17.6	9.7

DOE 5

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.7	11.2	23.2	12.0	13.4	12.1
Reading 2	6.0	10.8	21.9	10.8	13.8	7.1
Reading 3	5.5	7.7	18.2	9.3	10.1	4.7
Reading 4	4.3	8.1	18.4	10.2	11.1	4.8
Reading 5	5.4	8.3	18.8	10.4	12.7	5.3
Average	5.6	9.2	20.1	10.5	12.2	6.8
Cofficient of Variation	0.16	0.18	0.11	0.09	0.13	0.46

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.5	35.4	44.9	22.9	18.8	7.1
Reading 2	25.3	33.8	44.4	22.8	16.2	11.1
Reading 3	22.6	30.5	43.1	22.1	17.2	9.7
Reading 4	19.4	26.7	40.8	21.2	13.6	12.8
Reading 5	17.4	23.2	39.0	22.1	14.6	14.6
Average	22.0	29.9	42.4	22.2	16.1	11.1
Cofficient of Variation	0.16	0.17	0.06	0.03	0.13	0.26

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	12.4	26.4	19.3	20.4	11.2
Reading 2	6.5	12.6	25.9	19.8	21.5	11.4
Reading 3	6.5	12.2	26.5	19.5	18.7	6.0
Reading 4	7.2	12.4	28.2	19.2	19.5	6.4
Reading 5	6.0	11.9	25.0	18.3	18.1	11.2
Average	6.6	12.3	26.4	19.2	19.6	9.2
Cofficient of Variation	0.07	0.02	0.04	0.03	0.07	0.30

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.6	33.5	45.1	20.8	16.2	8.7
Reading 2	24.9	35.6	47.0	23.6	17.8	11.0
Reading 3	24.7	36.2	45.9	21.9	16.4	17.0
Reading 4	24.5	32.7	43.1	22.6	17.2	10.6
Reading 5	24.4	33.9	44.4	21.3	14.8	9.8
Average	24.8	34.4	45.1	22.0	16.5	11.4
Cofficient of Variation	0.02	0.04	0.03	0.05	0.07	0.28

Summary

H - CC	5.6	9.2	20.1	10.5	12.2	6.8
H - T	22.0	29.9	42.4	22.2	16.1	11.1
V - CC	6.6	12.3	26.4	19.2	19.6	9.2
V - T	24.8	34.4	45.1	22.0	16.5	11.4

DOE 19

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.1	14.3	28.5	13.6	14.8	6.9
Reading 2	5.4	10.8	23.8	13.5	13.9	9.2
Reading 3	6.2	8.5	21.1	10.7	13.0	9.8
Reading 4	5.6	8.4	19.9	10.5	14.4	8.2
Reading 5	5.6	9.3	20.4	12.5	15.7	10.3
Average	5.8	10.3	22.7	12.2	14.4	8.9
Cofficient of Variation	0.06	0.24	0.16	0.12	0.07	0.15

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.7	33.4	45.5	24.5	17.1	8.4
Reading 2	22.2	28.6	42.2	24.4	17.3	10.3
Reading 3	19.6	25.7	40.5	22.9	16.0	11.2
Reading 4	18.8	22.2	39.6	21.1	16.7	8.6
Reading 5	19.0	22.5	36.9	21.6	14.9	10.3
Average	20.9	26.5	40.9	22.9	16.4	9.8
Cofficient of Variation	0.12	0.18	0.08	0.07	0.06	0.12

Vertical - Clearcoat Only

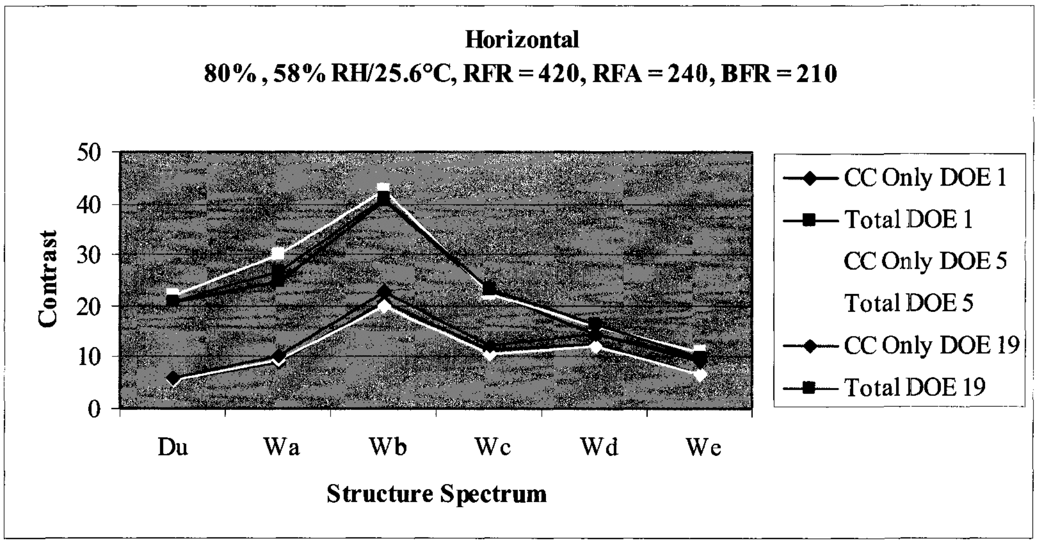
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	5.4	8.0	17.9	14.7	16.8	7.7
Reading 2	5.9	7.8	17.7	14.6	16.6	6.6
Reading 3	6.6	8.1	19.5	16.1	19.1	5.4
Reading 4	5.6	7.1	16.7	14.9	16.6	7.6
Reading 5	4.9	7.3	17.6	14.2	16.4	6.4
Average	5.7	7.7	17.9	14.9	17.1	6.7
Cofficient of Variation	0.11	0.06	0.06	0.05	0.07	0.14

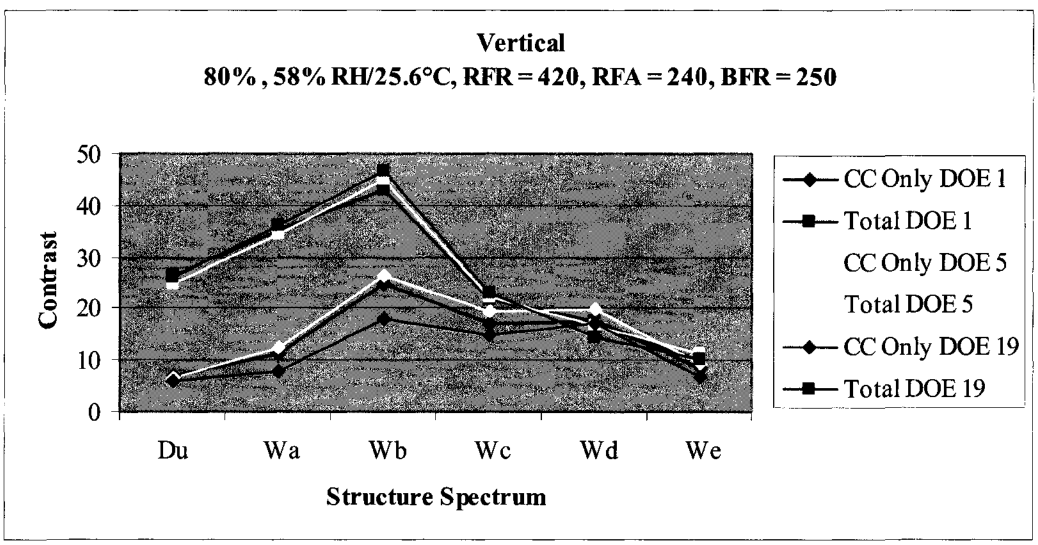
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.7	35.9	48.0	23.1	16.2	11.6
Reading 2	26.4	35.1	44.7	23.6	7.2	10.9
Reading 3	27.3	37.0	45.5	22.3	15.1	11.2
Reading 4	25.5	35.9	47.2	23.8	15.6	10.5
Reading 5	25.6	36.3	47.5	22.0	16.7	6.7
Average	26.1	36.0	46.6	23.0	14.2	10.2
Cofficient of Variation	0.03	0.02	0.03	0.03	0.28	0.20

Summary

H - CC	5.8	10.3	22.7	12.2	14.4	8.9
H - T	20.9	26.5	40.9	22.9	16.4	9.8
V - CC	5.7	7.7	17.9	14.9	17.1	6.7
V - T	26.1	36.0	46.6	23.0	14.2	10.2


Horizontal
80% , 58% RH/25.6°C, RFR = 420, RFA = 240, BFR = 210
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 1
Total DOE 1
CC Only DOE 5
Total DOE 5
CC Only DOE 19
Total DOE 19


Vertical
80% , 58% RH/25.6°C, RFR = 420, RFA = 240, BFR = 250
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 1
Total DOE 1
CC Only DOE 5
Total DOE 5
CC Only DOE 19
Total DOE 19

DOE 2

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	5.3	9.3	20.4	12.7	14.4	9.7
Reading 2	4.6	9.5	20.8	11.1	13.1	6.2
Reading 3	5.3	9.5	21.4	11.6	14.5	10.8
Reading 4	5.5	10.7	23.7	12.4	12.1	7.7
Reading 5	6.5	11.8	25.2	13.1	12.8	6.7
Average	5.4	10.2	22.3	12.2	13.4	8.2
Coefficient of Variation	0.68	0.11	0.09	0.07	0.08	0.24

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.0	28.0	38.8	17.4	14.3	9.9
Reading 2	21.8	26.2	36.7	17.7	13.3	8.1
Reading 3	21.8	26.4	36.5	17.1	12.8	8.5
Reading 4	21.6	25.9	39.7	17.6	12.8	11.9
Reading 5	20.6	25.7	40.1	18.6	12.6	10.0
Average	21.6	26.4	38.4	17.7	13.2	9.7
Coefficient of Variation	0.55	0.03	0.04	0.03	0.05	0.15

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.1	10.5	24.1	17.8	19.1	12.0
Reading 2	5.8	11.1	24.1	17.6	17.7	6.2
Reading 3	5.2	10.3	23.8	17.3	19.6	6.1
Reading 4	4.8	10.5	23.5	18.2	20.2	10.4
Reading 5	6.6	11.3	22.8	18.1	20.9	8.2
Average	5.7	10.7	23.7	17.8	19.5	8.6
Coefficient of Variation	0.71	0.04	0.02	0.02	0.06	0.30

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.8	32.4	40.6	20.8	18.7	13.8
Reading 2	24.9	30.6	40.4	20.8	19.7	6.9
Reading 3	24.2	31.1	40.7	21.2	15.1	9.8
Reading 4	24.3	31.1	42.5	20.3	17.6	13.7
Reading 5	25.2	32.9	42.6	20.4	16.6	11.7
Average	24.7	31.6	41.4	20.7	17.5	11.2
Coefficient of Variation	0.42	0.03	0.03	0.02	0.10	0.26

Summary

H - CC	5.4	10.2	22.3	12.2	13.4	8.2
H - T	21.6	26.4	38.4	17.7	13.2	9.7
V - CC	5.7	10.7	23.7	17.8	19.5	8.6
V - T	24.7	31.6	41.4	20.7	17.5	11.2

DOE 4

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.1	14.4	28.4	16.3	15.8	6.3
Reading 2	6.6	14.0	26.8	17.6	17.9	5.7
Reading 3	5.7	11.2	23.1	14.1	16.7	9.0
Reading 4	5.1	9.6	20.8	12.7	15.7	9.4
Reading 5	5.7	9.1	20.0	11.8	13.9	6.3
Average	6.0	11.7	23.8	14.5	16.0	7.3
Coefficient of Variation	0.80	0.21	0.15	0.17	0.09	0.23

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	20.4	24.9	40.0	21.0	13.5	10.3
Reading 2	20.9	26.9	39.6	20.4	14.9	9.3
Reading 3	22.3	28.0	38.0	20.1	15.0	9.3
Reading 4	20.7	25.3	35.8	18.9	13.0	8.7
Reading 5	21.6	24.5	36.3	17.9	13.5	6.3
Average	21.2	25.9	37.9	19.7	14.0	8.8
Coefficient of Variation	0.77	0.06	0.05	0.06	0.07	0.17

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	8.5	10.6	24.9	22.2	21.4	5.4
Reading 2	6.1	10.2	23.9	20.1	20.3	9.3
Reading 3	6.3	10.2	24.6	20.7	20.8	6.7
Reading 4	5.5	10.3	24.5	18.8	18.6	10.7
Reading 5	5.8	11.0	24.3	19.6	20.8	8.3
Average	6.4	10.5	24.4	20.3	20.4	8.1
Coefficient of Variation	1.19	0.03	0.02	0.06	0.05	0.26

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	29.5	37.1	40.1	22.1	19.6	7.8
Reading 2	29.6	36.1	39.7	23.9	22.1	8.8
Reading 3	28.2	35.4	40.2	21.6	21.5	10.6
Reading 4	27.6	36.2	40.1	21.9	17.1	8.5
Reading 5	25.8	34.4	41.5	20.7	23.2	7.8
Average	28.1	35.8	40.3	22.0	20.7	8.7
Coefficient of Variation	1.56	0.03	0.02	0.05	0.12	0.13

Summary

H - CC	6.0	11.7	23.8	14.5	16.0	7.3
H - T	21.2	25.9	37.9	19.7	14.0	8.8
V - CC	6.4	10.5	24.4	20.3	20.4	8.1
V - T	28.1	35.8	40.3	22.0	20.7	8.7

DOE 16

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.4	15.2	31.5	16.6	19.1	12.0
Reading 2	6.1	12.0	27.0	14.1	14.5	7.1
Reading 3	5.9	9.6	21.8	11.6	13.1	11.2
Reading 4	4.7	8.9	19.7	11.3	13.4	5.1
Reading 5	5.1	9.6	20.0	10.7	12.1	5.7
Average	5.8	11.1	24.0	12.9	14.4	8.2
Coefficient of Variation	1.04	0.23	0.21	0.19	0.19	0.39

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.6	28.4	39.4	19.1	16.1	8.4
Reading 2	21.0	26.4	39.3	19.1	15.8	8.9
Reading 3	20.7	24.8	38.5	16.4	15.0	7.9
Reading 4	20.2	25.6	37.0	17.7	11.8	4.0
Reading 5	21.0	24.0	37.4	17.8	14.5	13.4
Average	21.1	25.8	38.3	18.0	14.6	8.5
Coefficient of Variation	0.90	0.07	0.03	0.06	0.12	0.39

Vertical - Clearcoat Only

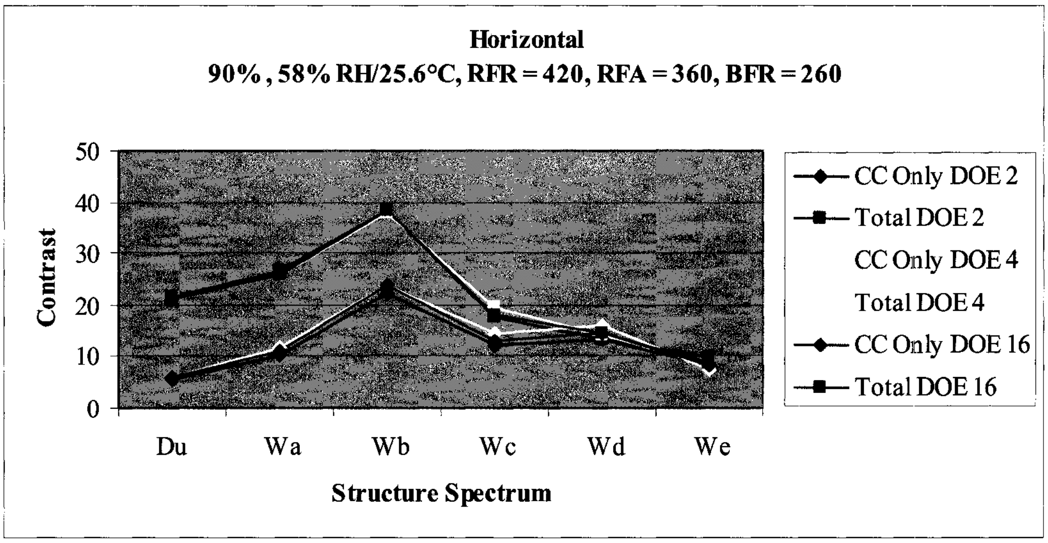
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.9	12.1	23.8	22.0	23.2	8.5
Reading 2	7.7	11.9	23.5	23.3	23.6	7.7
Reading 3	6.7	11.3	24.1	20.9	21.5	7.6
Reading 4	6.9	11.6	22.8	20.1	23.3	6.1
Reading 5	6.6	11.4	26.0	18.2	18.8	4.4
Average	7.2	11.7	24.0	20.9	22.1	6.9
Coefficient of Variation	0.60	0.03	0.05	0.09	0.09	0.24

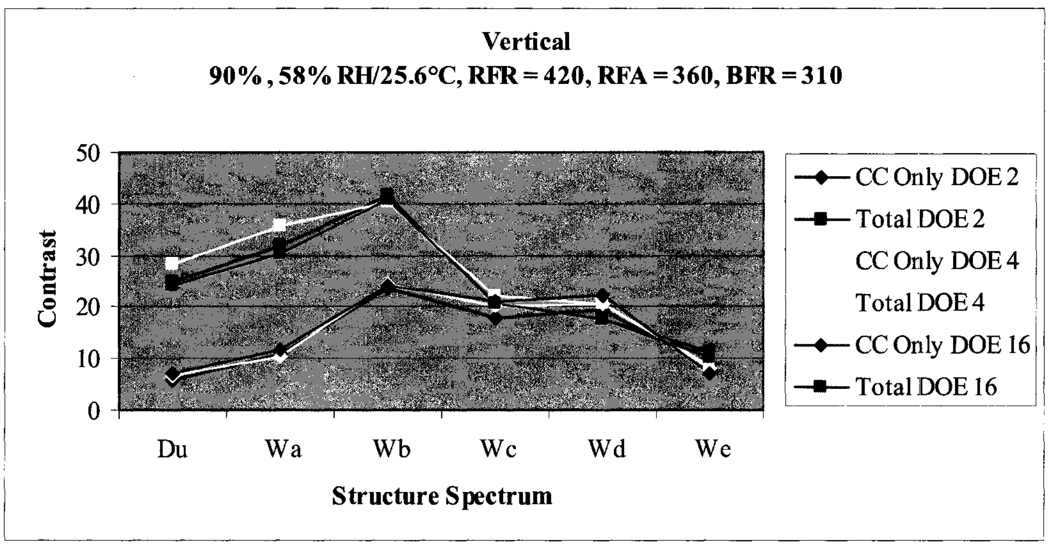
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.0	29.8	40.7	20.9	17.6	13.8
Reading 2	24.0	31.3	40.1	21.0	18.8	8.9
Reading 3	23.5	29.5	40.5	20.5	17.2	6.5
Reading 4	23.3	29.6	41.2	19.9	16.0	12.1
Reading 5	24.6	31.7	40.9	20.5	17.9	9.5
Average	23.9	30.4	40.7	20.6	17.5	10.2
Coefficient of Variation	0.51	0.03	0.01	0.02	0.06	0.28

Summary

H - CC	5.8	11.1	24.0	12.9	14.4	8.2
H - T	21.1	25.8	38.3	18.0	14.6	8.5
V - CC	7.2	11.7	24.0	20.9	22.1	6.9
V - T	23.9	30.4	40.7	20.6	17.5	10.2


Horizontal
90%, 58% RH/25.6°C, RFR = 420, RFA = 360, BFR = 260
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 2
Total DOE 2
CC Only DOE 4
Total DOE 4
CC Only DOE 16
Total DOE 16


Vertical
90%, 58% RH/25.6°C, RFR = 420, RFA = 360, BFR = 310
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 2
Total DOE 2
CC Only DOE 4
Total DOE 4
CC Only DOE 16
Total DOE 16

DOE 3

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.8	16.1	30.9	16.2	18.2	6.9
Reading 2	7.2	13.7	27.0	16.5	17.9	7.7
Reading 3	6.0	11.6	23.7	14.6	15.5	9.7
Reading 4	5.8	10.6	24.5	13.2	14.0	8.3
Reading 5	5.2	9.3	21.4	11.1	13.0	7.1
Average	6.4	12.3	25.5	14.3	15.7	7.9
Coefficient of Variation	1.07	0.22	0.14	0.16	0.15	0.14

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.0	28.6	40.2	19.1	13.9	4.5
Reading 2	21.4	25.8	37.4	18.1	13.5	7.4
Reading 3	19.3	24.1	37.9	17.9	12.3	6.6
Reading 4	19.2	25.0	39.6	19.0	11.6	11.0
Reading 5	20.0	24.2	38.0	16.3	11.3	6.7
Average	20.4	25.5	38.6	18.1	12.5	7.2
Coefficient of Variation	1.26	0.07	0.03	0.06	0.09	0.33

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.4	12.7	27.5	18.3	20.4	11.1
Reading 2	6.8	12.9	28.6	21.6	18.2	9.6
Reading 3	6.9	11.7	27.5	19.0	18.9	7.6
Reading 4	7.1	11.8	26.4	17.6	17.2	8.9
Reading 5	6.6	12.1	26.0	15.9	18.2	7.0
Average	7.0	12.2	27.2	18.5	18.6	8.8
Coefficient of Variation	0.30	0.04	0.04	0.11	0.06	0.18

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	27.2	32.3	35.7	22.5	20.1	10.3
Reading 2	27.0	32.8	38.7	20.9	18.6	14.2
Reading 3	25.5	31.1	31.1	20.8	17.2	6.4
Reading 4	26.0	30.6	30.6	21.5	20.4	9.3
Reading 5	26.2	33.1	37.6	20.6	19.1	5.9
Average	26.4	32.0	34.7	21.3	19.1	9.2
Coefficient of Variation	0.71	0.03	0.11	0.04	0.07	0.36

Summary

H - CC	6.4	12.3	25.5	14.3	15.7	7.9
H - T	20.4	25.5	38.6	18.1	12.5	7.2
V - CC	7.0	12.2	27.2	18.5	18.6	8.8
V - T	26.4	32.0	34.7	21.3	19.1	9.2

DOE 13

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.7	15.7	28.2	17.3	19.6	7.7
Reading 2	5.7	13.9	26.2	14.2	14.8	7.9
Reading 3	6.1	12.4	26.0	14.1	14.3	10.2
Reading 4	4.8	9.8	20.8	12.6	14.0	9.5
Reading 5	5.1	9.8	20.8	12.3	14.5	7.4
Average	5.9	12.3	24.4	14.1	15.4	8.5
Coefficient of Variation	1.14	0.21	0.14	0.14	0.15	0.14

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.2	25.5	39.0	17.7	13.7	9.4
Reading 2	22.0	26.9	37.3	18.2	14.0	7.9
Reading 3	22.5	27.0	34.7	17.3	17.9	9.7
Reading 4	21.6	25.2	36.2	17.5	14.2	6.4
Reading 5	21.2	23.1	36.6	16.2	13.3	11.0
Average	21.7	25.5	36.8	17.4	14.6	8.9
Coefficient of Variation	0.56	0.06	0.04	0.04	0.13	0.20

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	10.2	23.0	21.0	18.4	7.5
Reading 2	6.5	9.5	21.3	19.8	20.1	5.9
Reading 3	6.3	9.2	21.7	18.7	18.0	9.3
Reading 4	5.3	10.0	23.4	17.6	21.0	9.2
Reading 5	5.1	11.1	23.4	21.5	23.2	11.7
Average	6.0	10.0	22.6	19.7	20.1	8.7
Coefficient of Variation	0.71	0.07	0.04	0.08	0.10	0.25

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.1	30.1	36.7	20.6	19.0	8.3
Reading 2	23.0	29.2	33.8	18.4	20.1	10.0
Reading 3	23.1	27.8	34.8	18.6	16.3	5.3
Reading 4	21.8	26.4	34.3	16.7	16.2	9.4
Reading 5	21.0	28.4	36.3	16.8	13.1	14.2
Average	22.6	28.4	35.2	18.2	16.9	9.4
Coefficient of Variation	1.21	0.05	0.04	0.09	0.16	0.34

Summary

H - CC	5.9	12.3	24.4	14.1	15.4	8.5
H - T	21.7	25.5	36.8	17.4	14.6	8.9
V - CC	6.0	10.0	22.6	19.7	20.1	8.7
V - T	22.6	28.4	35.2	18.2	16.9	9.4

DOE 23

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	15.0	29.2	17.1	16.8	7.5
Reading 2	5.8	10.9	22.3	12.2	16.2	9.0
Reading 3	5.1	10.0	20.1	11.3	13.8	11.7
Reading 4	5.4	8.4	18.3	11.2	15.0	7.7
Reading 5	4.2	7.9	18.5	10.5	12.9	6.9
Average	5.4	10.4	21.7	12.5	14.9	8.6
Coefficient of Variation	0.88	0.27	0.21	0.21	0.11	0.22

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	19.7	24.9	38.0	18.0	14.4	7.9
Reading 2	18.9	22.1	34.7	16.2	13.2	7.3
Reading 3	19.6	23.3	34.7	16.6	13.4	7.9
Reading 4	19.6	23.4	34.3	16.1	12.4	8.0
Reading 5	19.2	23.1	33.2	15.9	12.8	5.7
Average	19.4	23.4	35.0	16.6	13.2	7.4
Coefficient of Variation	0.34	0.04	0.05	0.05	0.06	0.13

Vertical - Clearcoat Only

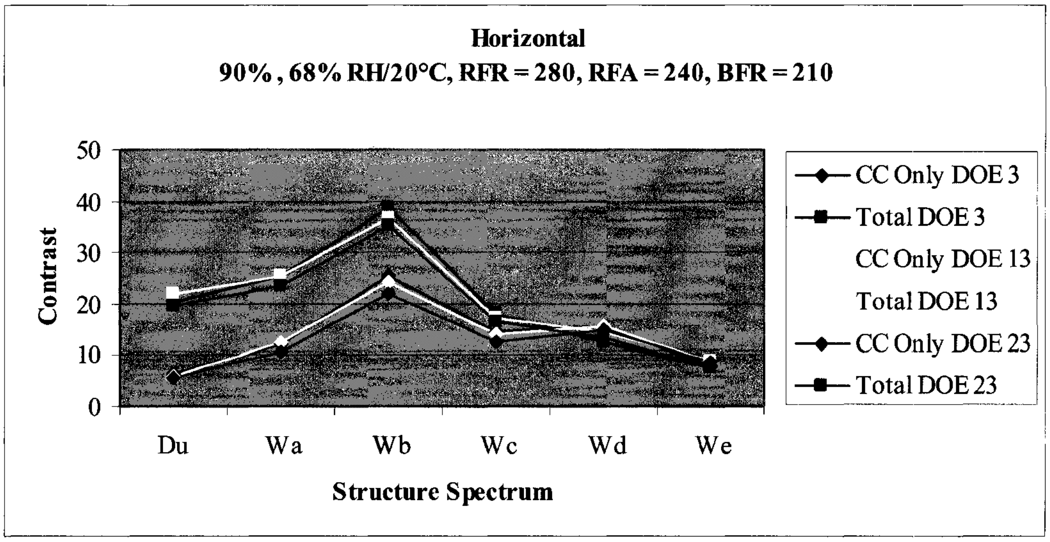
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	5.6	8.7	20.4	19.1	20.2	7.6
Reading 2	5.0	8.1	17.6	19.0	20.5	5.7
Reading 3	6.0	8.0	18.9	18.8	19.2	5.4
Reading 4	4.2	8.1	20.1	15.5	17.5	4.0
Reading 5	4.9	8.6	20.2	16.7	20.4	6.0
Average	5.1	8.3	19.4	17.8	19.6	5.7
Coefficient of Variation	0.69	0.04	0.06	0.09	0.06	0.23

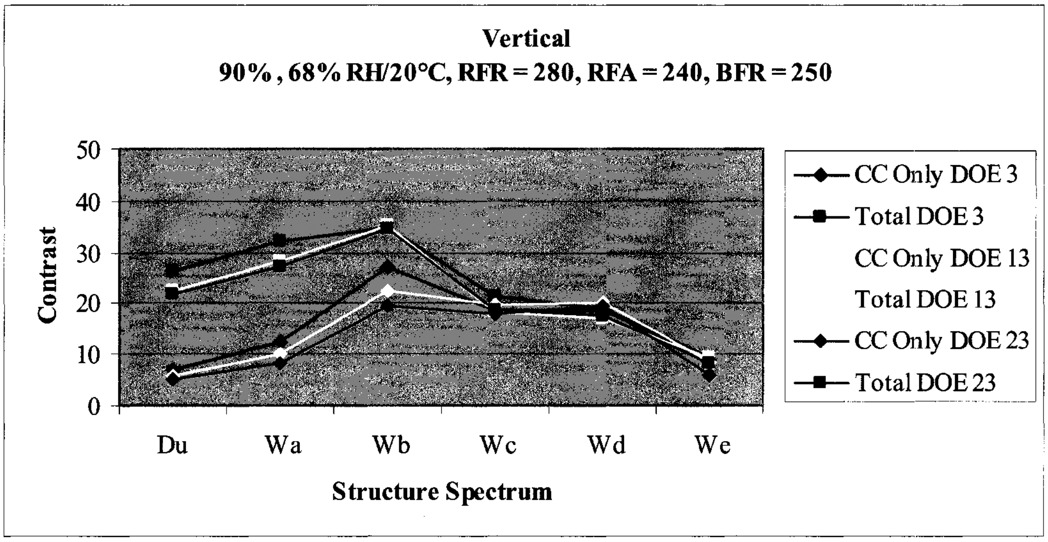
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	20.2	25.2	33.8	18.0	16.5	9.7
Reading 2	22.4	27.1	34.0	18.5	15.7	8.7
Reading 3	22.2	27.5	36.9	19.1	18.0	6.4
Reading 4	21.1	27.1	32.1	18.2	19.1	9.1
Reading 5	22.3	28.8	36.5	18.3	18.1	7.1
Average	21.6	27.1	34.7	18.4	17.5	8.2
Coefficient of Variation	0.96	0.05	0.06	0.02	0.08	0.17

Summary

H - CC	5.4	10.4	21.7	12.5	14.9	8.6
H - T	19.4	23.4	35.0	16.6	13.2	7.4
V - CC	5.1	8.3	19.4	17.8	19.6	5.7
V - T	21.6	27.1	34.7	18.4	17.5	8.2


Horizontal
90%, 68% RH/20°C, RFR = 280, RFA = 240, BFR = 210
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 3
Total DOE 3
CC Only DOE 13
Total DOE 13
CC Only DOE 23
Total DOE 23


Vertical
90%, 68% RH/20°C, RFR = 280, RFA = 240, BFR = 250
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 3
Total DOE 3
CC Only DOE 13
Total DOE 13
CC Only DOE 23
Total DOE 23

DOE 6

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.8	16.4	31.0	16.6	17.0	9.9
Reading 2	6.8	14.0	28.0	16.4	14.3	9.7
Reading 3	5.6	11.5	25.4	12.1	12.4	6.3
Reading 4	6.0	10.0	23.5	10.9	11.6	6.7
Reading 5	5.8	9.1	21.7	12.1	9.3	9.2
Average	6.4	12.2	25.9	13.6	12.9	8.4
Coefficient of Variation	0.91	0.25	0.14	0.20	0.22	0.21

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.6	29.2	43.1	20.5	15.9	11.0
Reading 2	22.1	28.7	41.0	20.0	14.8	7.0
Reading 3	22.0	26.4	38.5	19.6	14.5	7.1
Reading 4	20.2	24.4	38.0	18.8	13.2	8.0
Reading 5	21.2	24.1	35.7	18.9	13.9	11.9
Average	21.6	26.6	39.3	19.6	14.5	9.0
Coefficient of Variation	0.94	0.09	0.07	0.04	0.07	0.25

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	8.3	12.0	25.2	17.9	19.9	7.1
Reading 2	7.4	12.4	25.7	22.9	22.9	8.0
Reading 3	6.7	12.3	25.1	18.9	20.6	7.2
Reading 4	7.5	12.6	26.3	17.7	17.1	6.0
Reading 5	6.0	12.5	25.8	18.5	17.9	8.6
Average	7.2	12.4	25.6	19.2	19.7	7.4
Coefficient of Variation	0.87	0.02	0.02	0.11	0.12	0.13

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	23.3	32.2	42.6	20.9	15.9	9.9
Reading 2	24.7	32.5	40.1	21.2	15.7	10.9
Reading 3	25.6	34.1	42.0	21.8	15.7	7.7
Reading 4	24.8	33.4	42.9	20.9	14.1	8.4
Reading 5	24.5	33.4	42.6	21.2	15.1	8.5
Average	24.6	33.1	42.0	21.2	15.3	9.1
Coefficient of Variation	0.83	0.02	0.03	0.02	0.05	0.14

Summary

H - CC	6.4	12.2	25.9	13.6	12.9	8.4
H - T	21.6	26.6	39.3	19.6	14.5	9.0
V - CC	7.2	12.4	25.6	19.2	19.7	7.4
V - T	24.6	33.1	42.0	21.2	15.3	9.1

DOE 21

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.2	15.8	32.6	17.2	15.7	7.0
Reading 2	5.9	12.2	27.8	14.0	14.2	7.9
Reading 3	7.6	10.3	24.9	11.6	10.5	9.3
Reading 4	5.7	9.9	24.6	12.6	17.6	11.7
Reading 5	5.8	10.4	23.7	13.2	12.8	7.1
Average	6.4	11.7	26.7	13.7	14.2	8.6
Coefficient of Variation	0.89	0.21	0.14	0.16	0.19	0.23

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.7	31.4	43.5	20.9	17.3	10.3
Reading 2	23.7	30.5	38.9	19.6	15.6	11.3
Reading 3	22.1	28.4	40.0	20.6	14.1	12.8
Reading 4	18.7	22.1	37.8	20.0	14.8	9.0
Reading 5	19.3	20.6	36.1	17.7	10.4	8.7
Average	21.7	26.6	39.3	19.8	14.4	10.4
Coefficient of Variation	2.64	0.19	0.07	0.06	0.18	0.16

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.7	11.7	23.2	21.2	21.7	4.4
Reading 2	6.5	11.0	23.3	22.3	21.2	8.5
Reading 3	7.4	11.4	23.5	20.8	20.1	10.9
Reading 4	7.4	12.4	26.4	21.2	22.7	9.6
Reading 5	6.7	11.5	25.3	22.4	21.8	5.4
Average	6.9	11.6	24.3	21.6	21.5	7.8
Coefficient of Variation	0.43	0.04	0.06	0.03	0.04	0.36

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.2	31.1	41.8	21.1	14.2	8.7
Reading 2	23.3	32.0	40.7	20.9	14.3	7.1
Reading 3	25.6	33.0	42.8	20.9	15.3	7.2
Reading 4	25.8	33.8	41.5	21.5	16.2	7.6
Reading 5	22.4	32.0	40.7	21.1	15.9	10.7
Average	24.3	32.4	41.5	21.1	15.2	8.3
Coefficient of Variation	1.46	0.03	0.02	0.01	0.06	0.18

Summary

H - CC	6.4	11.7	26.7	13.7	14.2	8.6
H - T	21.7	26.6	39.3	19.8	14.4	10.4
V - CC	6.9	11.6	24.3	21.6	21.5	7.8
V - T	24.3	32.4	41.5	21.1	15.2	8.3

DOE 24

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	9.7	19.8	34.0	20.8	19.7	8.5
Reading 2	8.5	16.8	30.0	19.8	21.9	8.8
Reading 3	7.8	16.5	27.7	18.8	19.9	13.5
Reading 4	7.1	12.1	24.8	15.4	15.1	7.7
Reading 5	6.9	11.2	22.9	14.6	16.4	7.3
Average	8.0	15.3	27.9	17.9	18.6	9.2
Coefficient of Variation	1.14	0.23	0.16	0.15	0.15	0.27

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	19.5	27.0	41.9	19.5	13.3	8.5
Reading 2	20.0	23.9	37.3	20.1	12.5	9.4
Reading 3	20.1	24.1	38.2	19.6	12.5	10.5
Reading 4	20.5	24.4	35.6	18.0	13.1	9.7
Reading 5	21.4	23.8	36.6	18.4	13.0	6.7
Average	20.3	24.6	37.9	19.1	12.9	9.0
Coefficient of Variation	0.71	0.05	0.06	0.05	0.03	0.16

Vertical - Clearcoat Only

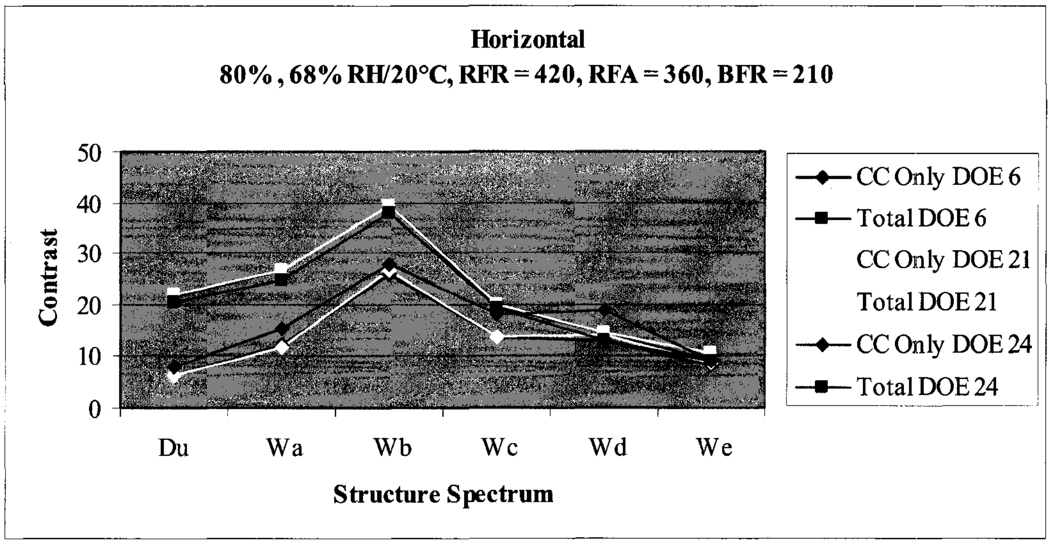
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	12.1	26.5	18.9	17.1	8.0
Reading 2	8.3	12.6	26.1	19.6	19.0	8.0
Reading 3	6.4	12.9	27.1	19.8	19.0	10.3
Reading 4	6.7	10.8	22.9	17.9	17.9	5.3
Reading 5	7.4	11.0	24.0	16.3	16.3	8.5
Average	7.1	11.9	25.3	18.5	17.9	8.0
Coefficient of Variation	0.78	0.08	0.07	0.08	0.07	0.22

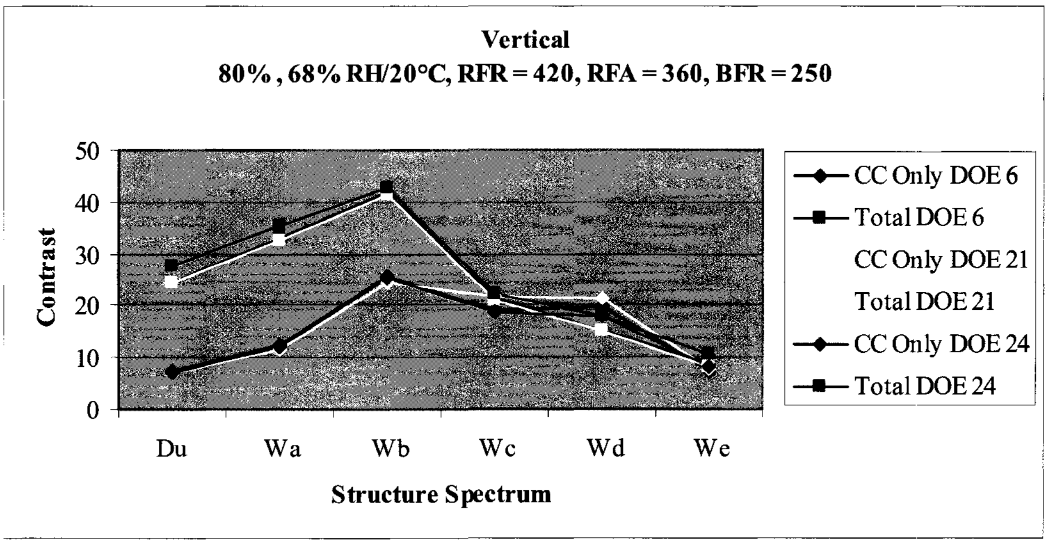
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	26.7	34.9	41.7	21.8	17.7	8.5
Reading 2	26.2	34.4	42.0	21.3	20.0	9.3
Reading 3	27.4	34.0	42.1	22.4	16.8	11.2
Reading 4	28.4	35.4	43.8	23.1	17.2	11.6
Reading 5	28.0	37.6	42.7	21.5	18.2	11.4
Average	27.3	35.3	42.5	22.0	18.0	10.4
Coefficient of Variation	0.90	0.04	0.02	0.03	0.07	0.14

Summary

H - CC	8.0	15.3	27.9	17.9	18.6	9.2
H - T	20.3	24.6	37.9	19.1	12.9	9.0
V - CC	7.1	11.9	25.3	18.5	17.9	8.0
V - T	27.3	35.3	42.5	22.0	18.0	10.4


Horizontal
80%, 68% RH/20°C, RFR = 420, RFA = 360, BFR = 210
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 6
Total DOE 6
CC Only DOE 21
Total DOE 21
CC Only DOE 24
Total DOE 24


Vertical
80%, 68% RH/20°C, RFR = 420, RFA = 360, BFR = 250
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 6
Total DOE 6
CC Only DOE 21
Total DOE 21
CC Only DOE 24
Total DOE 24

DOE 7

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.5	16.4	31.8	16.8	14.0	8.7
Reading 2	7.8	14.4	29.0	15.2	16.4	9.2
Reading 3	6.8	13.0	29.2	13.6	11.0	6.6
Reading 4	5.4	9.7	23.5	11.4	10.4	7.5
Reading 5	5.9	10.3	23.0	12.2	13.5	8.4
Average	6.7	12.8	27.3	13.8	13.1	8.1
Coefficient of Variation	1.02	0.22	0.14	0.16	0.19	0.13

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.2	27.5	39.2	20.8	14.5	11.2
Reading 2	22.1	27.8	41.1	21.3	15.0	11.7
Reading 3	21.5	24.4	36.9	19.3	13.6	10.2
Reading 4	20.7	25.4	37.7	18.9	12.8	8.3
Reading 5	20.8	24.0	35.1	19.8	13.5	12.1
Average	21.5	25.8	38.0	20.0	13.9	10.7
Coefficient of Variation	0.70	0.07	0.06	0.05	0.06	0.14

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.4	11.3	26.0	16.0	16.5	6.4
Reading 2	6.2	11.1	25.4	16.7	18.3	7.9
Reading 3	6.8	11.4	26.4	17.0	17.4	8.6
Reading 4	6.7	10.1	21.9	17.8	17.0	5.2
Reading 5	6.1	10.6	24.6	17.4	18.4	8.5
Average	6.4	10.9	24.9	17.0	17.5	7.3
Coefficient of Variation	0.30	0.05	0.07	0.04	0.05	0.20

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	27.3	36.2	42.3	20.9	15.8	9.2
Reading 2	27.3	36.1	40.9	21.9	16.4	10.1
Reading 3	28.2	35.9	41.9	20.4	15.1	9.0
Reading 4	27.3	35.4	42.6	21.5	14.3	11.3
Reading 5	27.3	34.2	42.9	21.6	14.3	5.2
Average	27.5	35.6	42.1	21.3	15.2	9.0
Coefficient of Variation	0.40	0.02	0.02	0.03	0.06	0.26

Summary

H - CC	6.7	12.8	27.3	13.8	13.1	8.1
H - T	21.5	25.8	38.0	20.0	13.9	10.7
V - CC	6.4	10.9	24.9	17.0	17.5	7.3
V - T	27.5	35.6	42.1	21.3	15.2	9.0

DOE 8

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.0	12.4	25.1	13.3	11.8	10.5
Reading 2	5.8	10.6	23.3	12.9	10.7	6.7
Reading 3	6.1	10.4	23.0	12.3	12.7	8.8
Reading 4	6.0	9.3	21.8	11.1	12.1	15.4
Reading 5	5.5	8.8	21.2	13.5	13.4	8.8
Average	5.9	10.3	22.9	12.6	12.1	10.0
Coefficient of Variation	0.24	0.14	0.07	0.08	0.08	0.33

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	20.8	25.0	38.7	20.4	14.6	9.7
Reading 2	22.1	25.7	37.1	18.8	14.3	6.3
Reading 3	21.1	26.3	39.0	19.0	14.6	10.1
Reading 4	21.1	25.7	39.6	18.4	13.2	10.9
Reading 5	21.0	24.9	35.7	19.1	9.6	10.2
Average	21.2	25.5	38.0	19.1	13.3	9.4
Coefficient of Variation	0.51	0.02	0.04	0.04	0.16	0.19

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	12.6	25.5	18.9	18.2	7.9
Reading 2	7.8	10.7	22.5	17.9	20.1	10.4
Reading 3	7.1	12.0	25.5	18.4	18.1	7.8
Reading 4	6.7	11.0	24.3	17.4	17.6	10.6
Reading 5	6.3	10.8	23.5	16.4	16.4	9.6
Average	6.9	11.4	24.3	17.8	18.1	9.3
Coefficient of Variation	0.58	0.07	0.05	0.05	0.07	0.14

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.5	33.7	42.7	20.8	15.0	4.7
Reading 2	26.4	33.0	42.2	21.0	16.4	6.9
Reading 3	24.5	32.4	40.4	20.0	15.7	10.1
Reading 4	25.4	32.5	42.8	19.5	15.2	10.4
Reading 5	22.9	30.7	42.9	20.5	13.2	8.8
Average	24.7	32.5	42.2	20.4	15.1	8.2
Coefficient of Variation	1.29	0.03	0.02	0.03	0.08	0.29

Summary

H - CC	5.9	10.3	22.9	12.6	12.1	10.0
H - T	21.2	25.5	38.0	19.1	13.3	9.4
V - CC	6.9	11.4	24.3	17.8	18.1	9.3
V - T	24.7	32.5	42.2	20.4	15.1	8.2

DOE 18

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	14.2	29.6	14.4	15.7	10.7
Reading 2	5.8	12.5	28.2	13.5	12.8	6.5
Reading 3	5.1	8.7	22.3	12.0	12.0	9.9
Reading 4	5.3	8.3	21.7	11.0	11.0	5.2
Reading 5	4.7	9.5	19.9	11.3	13.8	10.8
Average	5.6	10.6	24.3	12.4	13.1	8.6
Coefficient of Variation	0.85	0.24	0.18	0.12	0.14	0.30

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.0	29.7	40.0	21.4	15.9	14.4
Reading 2	24.7	30.4	40.6	21.0	16.3	9.6
Reading 3	22.5	29.3	38.0	20.3	13.4	7.3
Reading 4	19.8	24.5	36.3	18.0	13.5	12.0
Reading 5	19.1	22.1	33.3	16.4	13.9	7.5
Average	22.0	27.2	37.6	19.4	14.6	10.2
Coefficient of Variation	2.49	0.14	0.08	0.11	0.10	0.30

Vertical - Clearcoat Only

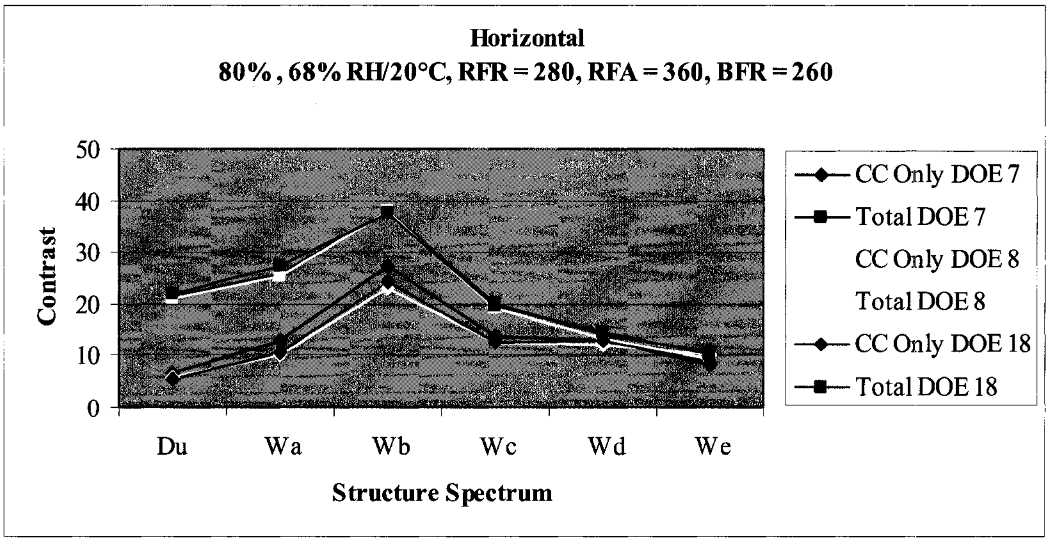
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.6	11.5	23.5	18.8	19.2	4.9
Reading 2	6.4	11.9	24.8	21.3	20.0	11.2
Reading 3	6.8	11.4	24.1	20.6	18.8	3.3
Reading 4	6.2	12.6	25.3	18.2	18.1	7.7
Reading 5	6.8	11.3	24.7	16.1	17.1	7.5
Average	6.6	11.7	24.5	19.0	18.6	6.9
Coefficient of Variation	0.26	0.05	0.03	0.11	0.06	0.44

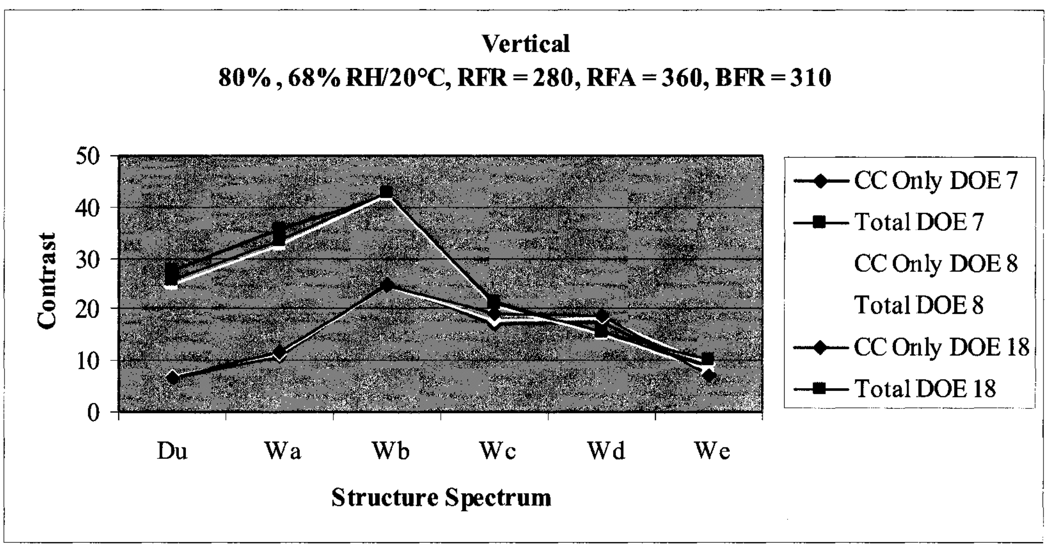
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.4	33.5	41.1	20.0	15.1	10.1
Reading 2	26.3	34.3	41.3	22.6	13.9	9.3
Reading 3	26.9	33.3	44.2	20.7	15.2	8.2
Reading 4	25.6	32.6	41.5	21.6	16.2	10.2
Reading 5	23.9	33.8	44.9	19.9	16.5	11.8
Average	25.6	33.5	42.6	21.0	15.4	9.9
Coefficient of Variation	1.13	0.02	0.04	0.05	0.07	0.13

Summary

H - CC	5.6	10.6	24.3	12.4	13.1	8.6
H - T	22.0	27.2	37.6	19.4	14.6	10.2
V - CC	6.6	11.7	24.5	19.0	18.6	6.9
V - T	25.6	33.5	42.6	21.0	15.4	9.9


Horizontal
80%, 68% RH/20°C, RFR = 280, RFA = 360, BFR = 260
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 7
Total DOE 7
CC Only DOE 8
Total DOE 8
CC Only DOE 18
Total DOE 18


Vertical
80%, 68% RH/20°C, RFR = 280, RFA = 360, BFR = 310
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 7
Total DOE 7
CC Only DOE 8
Total DOE 8
CC Only DOE 18
Total DOE 18

DOE 9

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.4	13.4	28.1	13.2	11.7	4.9
Reading 2	5.0	11.4	25.6	12.3	12.8	5.8
Reading 3	4.8	8.9	20.8	10.8	12.5	7.9
Reading 4	3.8	8.3	20.0	10.2	10.5	8.8
Reading 5	5.1	7.7	20.0	9.4	8.8	7.4
Average	5.0	9.9	22.9	11.2	11.3	7.0
Coefficient of Variation	0.93	0.24	0.16	0.14	0.15	0.23

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	19.5	23.2	39.4	18.0	13.7	10.2
Reading 2	19.3	23.7	40.1	19.1	11.9	7.9
Reading 3	20.0	24.2	37.0	17.8	12.8	10.8
Reading 4	20.7	23.6	37.7	18.0	12.6	8.7
Reading 5	20.8	25.0	41.2	17.6	12.9	7.4
Average	20.1	23.9	39.1	18.1	12.8	9.0
Coefficient of Variation	0.68	0.03	0.04	0.03	0.05	0.16

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.3	11.8	25.1	23.0	24.1	5.7
Reading 2	6.1	10.4	22.3	20.2	23.6	11.3
Reading 3	6.4	10.3	21.8	19.1	19.4	11.4
Reading 4	6.5	10.4	22.8	19.5	22.9	8.1
Reading 5	7.1	9.9	22.8	17.4	20.9	5.0
Average	6.5	10.6	23.0	19.8	22.2	8.3
Coefficient of Variation	0.38	0.07	0.06	0.10	0.09	0.36

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.7	29.1	38.8	18.8	18.0	11.9
Reading 2	25.9	29.8	35.6	19.6	17.7	6.0
Reading 3	25.3	29.6	36.6	20.7	18.6	9.0
Reading 4	24.1	29.8	37.7	18.6	15.6	12.1
Reading 5	22.9	28.6	38.1	19.1	15.5	8.3
Average	24.6	29.4	37.4	19.4	17.1	9.5
Coefficient of Variation	1.15	0.02	0.03	0.04	0.08	0.27

Summary

H - CC	5.0	9.9	22.9	11.2	11.3	7.0
H - T	20.1	23.9	39.1	18.1	12.8	9.0
V - CC	6.5	10.6	23.0	19.8	22.2	8.3
V - T	24.6	29.4	37.4	19.4	17.1	9.5

DOE 11

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.5	12.3	22.9	15.7	19.3	9.9
Reading 2	6.4	10.4	21.6	14.8	18.7	6.5
Reading 3	4.4	8.4	18.4	11.2	12.7	8.5
Reading 4	5.1	7.8	17.1	10.1	10.5	9.7
Reading 5	4.3	7.7	19.0	10.2	12.2	7.5
Average	5.3	9.3	19.8	12.4	14.7	8.4
Coefficient of Variation	1.06	0.21	0.12	0.21	0.27	0.17

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.4	25.0	37.3	17.3	12.6	8.9
Reading 2	21.2	24.4	38.4	16.5	12.0	8.0
Reading 3	20.7	23.5	37.4	16.5	12.5	3.9
Reading 4	19.7	24.4	39.5	16.1	10.4	7.1
Reading 5	20.1	21.5	39.9	18.1	10.9	7.3
Average	20.6	23.8	38.5	16.9	11.7	7.0
Coefficient of Variation	0.72	0.06	0.03	0.05	0.08	0.27

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.0	10.9	21.7	22.7	19.7	5.2
Reading 2	7.2	9.3	19.4	20.3	21.6	4.7
Reading 3	5.8	8.2	18.6	19.0	20.1	7.3
Reading 4	5.9	9.0	20.6	18.9	18.4	4.0
Reading 5	5.4	9.5	19.2	18.3	21.1	9.0
Average	6.1	9.4	19.9	19.8	20.2	6.0
Coefficient of Variation	0.68	0.10	0.06	0.09	0.06	0.34

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	23.7	28.4	35.5	17.8	17.0	7.1
Reading 2	23.5	28.9	34.4	18.6	18.6	6.5
Reading 3	23.5	28.2	34.8	15.7	15.9	9.0
Reading 4	23.2	28.6	35.0	19.1	18.7	5.4
Reading 5	22.8	28.7	36.0	18.8	17.4	7.0
Average	23.3	28.6	35.1	18.0	17.5	7.0
Coefficient of Variation	0.35	0.01	0.02	0.08	0.07	0.19

Summary

H - CC	5.3	9.3	19.8	12.4	14.7	8.4
H - T	20.6	23.8	38.5	16.9	11.7	7.0
V - CC	6.1	9.4	19.9	19.8	20.2	6.0
V - T	23.3	28.6	35.1	18.0	17.5	7.0

DOE 15

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.4	15.5	29.7	16.8	18.5	6.4
Reading 2	7.2	14.3	25.7	15.9	16.8	7.5
Reading 3	5.6	11.5	24.8	14.6	15.9	7.7
Reading 4	6.0	11.1	23.5	12.6	15.9	9.7
Reading 5	6.5	9.4	20.1	12.1	17.3	8.7
Average	6.5	12.4	24.8	14.4	16.9	8.0
Coefficient of Variation	0.77	0.20	0.14	0.14	0.06	0.16

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.4	27.1	38.8	19.6	13.6	9.1
Reading 2	22.0	27.7	41.0	18.7	14.5	7.8
Reading 3	21.7	26.9	39.1	18.3	15.2	10.5
Reading 4	21.3	24.9	39.3	17.7	16.0	6.3
Reading 5	20.8	25.7	40.6	17.2	13.4	7.6
Average	21.6	26.5	39.8	18.3	14.5	8.3
Coefficient of Variation	0.62	0.04	0.02	0.05	0.07	0.19

Vertical - Clearcoat Only

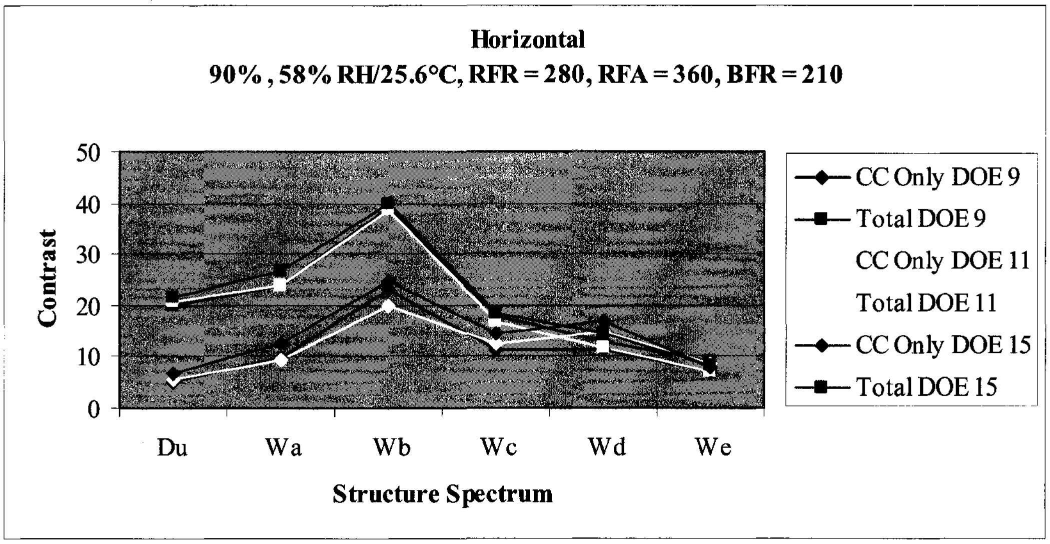
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	8.0	11.9	23.2	22.5	23.1	9.1
Reading 2	6.1	11.6	25.1	21.3	22.3	9.3
Reading 3	7.0	12.5	24.9	21.1	20.4	6.9
Reading 4	6.2	11.5	24.8	21.3	21.4	6.8
Reading 5	5.3	10.5	24.6	19.7	19.0	8.4
Average	6.5	11.6	24.5	21.2	21.2	8.1
Coefficient of Variation	1.02	0.06	0.03	0.05	0.08	0.15

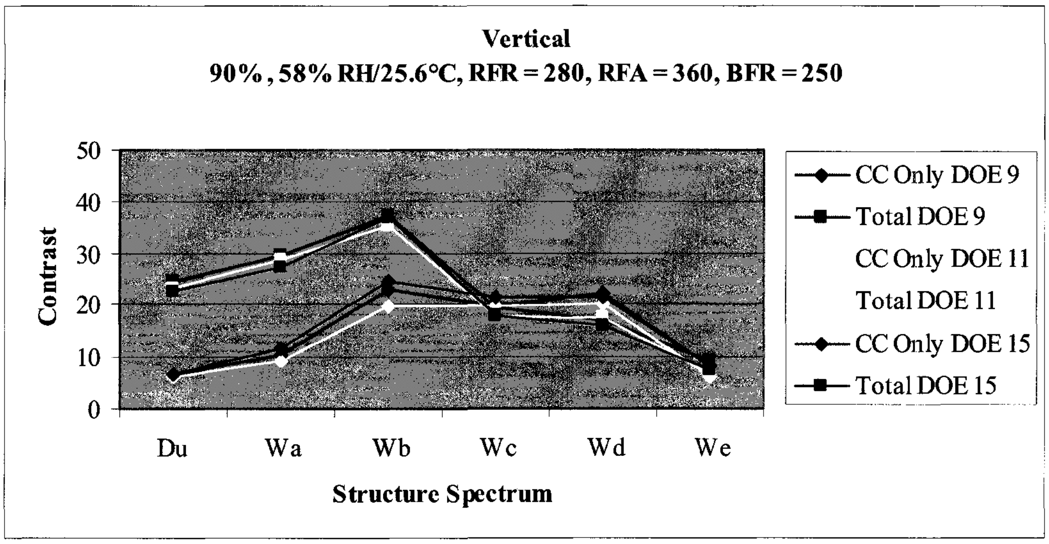
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.1	26.6	37.8	18.0	15.8	10.1
Reading 2	23.2	26.0	37.1	18.7	16.7	8.1
Reading 3	23.1	27.4	36.8	18.9	14.7	6.2
Reading 4	22.2	27.6	35.8	17.8	14.4	7.1
Reading 5	22.2	27.6	36.0	16.6	17.2	4.8
Average	22.6	27.0	36.7	18.0	15.8	7.3
Coefficient of Variation	0.54	0.03	0.02	0.05	0.08	0.28

Summary

H - CC	6.5	12.4	24.8	14.4	16.9	8.0
H - T	21.6	26.5	39.8	18.3	14.5	8.3
V - CC	6.5	11.6	24.5	21.2	21.2	8.1
V - T	22.6	27.0	36.7	18.0	15.8	7.3


Horizontal
90% , 58% RH/25.6°C, RFR = 280, RFA = 360, BFR = 210
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 9
Total DOE 9
CC Only DOE 11
Total DOE 11
CC Only DOE 15
Total DOE 15


Vertical
90% , 58% RH/25.6°C, RFR = 280, RFA = 360, BFR = 250
Contrast
50
40
30
20
10
0
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 9
Total DOE 9
CC Only DOE 11
Total DOE 11
CC Only DOE 15
Total DOE 15

DOE 10

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.9	13.4	28.0	13.3	12.0	4.5
Reading 2	5.5	12.0	25.6	13.4	14.3	10.5
Reading 3	5.6	10.8	24.7	13.6	13.3	7.7
Reading 4	6.0	10.4	24.0	11.8	12.1	8.9
Reading 5	6.0	11.2	24.0	13.8	16.0	9.7
Average	6.0	11.6	25.3	13.2	13.5	8.3
Coefficient of Variation	0.55	0.10	0.07	0.06	0.12	0.28

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	23.2	31.0	43.1	23.1	15.9	14.4
Reading 2	22.1	29.7	44.5	22.3	15.0	9.8
Reading 3	21.7	25.1	37.6	19.7	16.0	16.2
Reading 4	18.5	23.6	38.3	20.6	11.1	10.5
Reading 5	19.3	24.1	37.7	19.4	12.2	10.2
Average	21.0	26.7	40.2	21.0	14.0	12.2
Coefficient of Variation	1.98	0.13	0.08	0.08	0.16	0.24

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.7	10.6	23.4	18.8	17.8	7.6
Reading 2	5.8	10.7	23.5	20.5	21.7	9.7
Reading 3	5.3	10.6	22.4	18.6	20.6	12.1
Reading 4	6.9	10.6	24.6	16.7	18.6	6.7
Reading 5	6.2	9.9	22.2	17.0	17.6	5.7
Average	6.2	10.5	23.2	18.3	19.3	8.4
Coefficient of Variation	0.65	0.03	0.04	0.08	0.09	0.31

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.0	34.0	44.7	22.8	12.9	11.4
Reading 2	25.5	33.4	41.1	20.9	15.8	0.2
Reading 3	25.8	34.5	43.7	21.1	17.3	11.2
Reading 4	24.3	33.1	41.6	21.1	17.2	5.4
Reading 5	25.0	35.1	44.8	22.8	16.1	10.4
Average	25.1	34.0	43.2	21.7	15.9	7.7
Coefficient of Variation	0.57	0.02	0.04	0.04	0.11	0.63

Summary

H - CC	6.0	11.6	25.3	13.2	13.5	8.3
H - T	21.0	26.7	40.2	21.0	14.0	12.2
V - CC	6.2	10.5	23.2	18.3	19.3	8.4
V - T	25.1	34.0	43.2	21.7	15.9	7.7

DOE 12

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.1	12.9	26.1	12.6	13.0	4.7
Reading 2	5.7	11.9	24.8	12.7	13.7	10.1
Reading 3	5.9	8.8	20.9	10.2	10.4	8.8
Reading 4	5.2	9.7	20.5	11.1	10.7	9.5
Reading 5	5.0	8.7	19.8	10.1	11.5	6.4
Average	5.6	10.4	22.4	11.3	11.9	7.9
Coefficient of Variation	0.47	0.18	0.13	0.11	0.12	0.29

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.0	29.0	42.0	23.4	16.0	4.8
Reading 2	22.2	28.5	41.9	21.9	15.5	8.0
Reading 3	20.7	25.2	38.8	22.1	14.6	11.1
Reading 4	20.0	25.9	37.9	19.7	13.7	10.8
Reading 5	20.5	25.9	38.4	20.2	12.6	10.5
Average	21.1	26.9	39.8	21.5	14.5	9.0
Coefficient of Variation	0.97	0.06	0.05	0.07	0.09	0.30

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.4	11.1	24.1	16.9	18.3	7.9
Reading 2	6.3	10.6	23.6	19.2	17.6	8.4
Reading 3	7.3	10.4	23.6	17.9	18.6	9.0
Reading 4	6.7	11.1	23.1	18.1	17.5	6.8
Reading 5	5.3	10.2	22.1	16.7	18.5	12.2
Average	6.4	10.7	23.3	17.8	18.1	8.9
Coefficient of Variation	0.73	0.04	0.03	0.06	0.03	0.23

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	27.7	36.4	43.6	22.4	18.1	11.6
Reading 2	27.8	35.7	39.8	21.7	16.4	12.8
Reading 3	28.3	37.3	42.4	21.4	21.0	6.4
Reading 4	27.2	36.1	45.8	21.6	17.2	13.9
Reading 5	25.0	33.8	44.4	21.7	16.3	7.3
Average	27.2	35.9	43.2	21.8	17.8	10.4
Coefficient of Variation	1.29	0.04	0.05	0.02	0.11	0.32

Summary

H - CC	5.6	10.4	22.4	11.3	11.9	7.9
H - T	21.1	26.9	39.8	21.5	14.5	9.0
V - CC	6.4	10.7	23.3	17.8	18.1	8.9
V - T	27.2	35.9	43.2	21.8	17.8	10.4

DOE 14

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.5	14.6	30.4	14.1	13.5	6.1
Reading 2	5.6	12.1	26.3	12.9	12.3	8.9
Reading 3	6.8	11.4	24.1	12.6	10.5	8.9
Reading 4	6.8	10.5	23.4	12.1	12.1	4.7
Reading 5	6.0	12.0	25.4	13.6	13.4	6.7
Average	6.3	12.1	25.9	13.1	12.4	7.1
Coefficient of Variation	0.53	0.13	0.11	0.06	0.10	0.26

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.6	32.7	44.2	22.4	13.9	13.0
Reading 2	24.1	32.3	43.5	22.0	13.0	5.8
Reading 3	20.6	27.3	42.2	21.2	17.8	11.1
Reading 4	19.9	23.7	39.1	20.2	13.7	10.4
Reading 5	19.1	24.7	40.5	19.5	11.5	11.4
Average	21.9	28.1	41.9	21.1	14.0	10.3
Coefficient of Variation	2.83	0.15	0.05	0.06	0.17	0.26

Vertical - Clearcoat Only

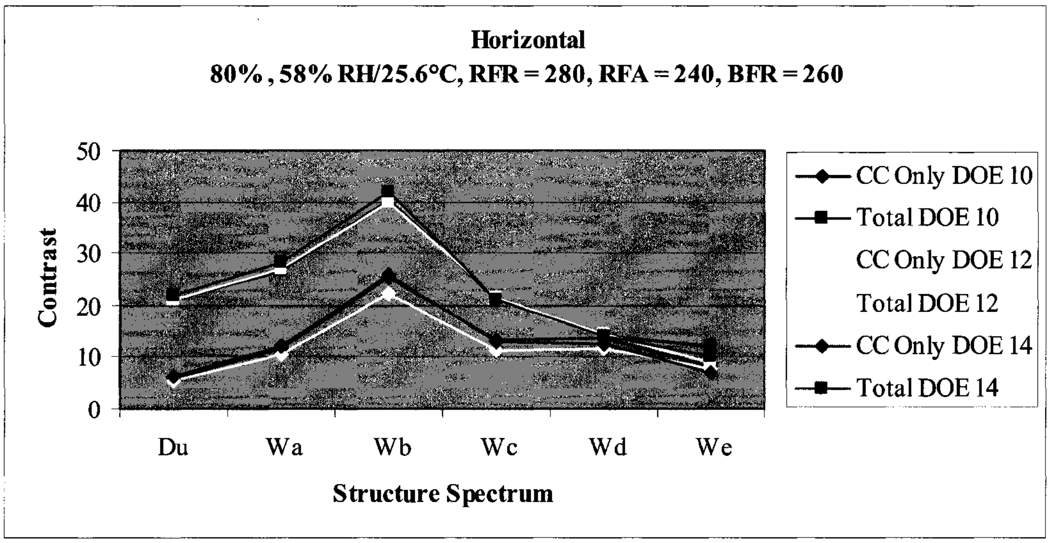
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.4	12.7	26.5	22.4	23.1	8.8
Reading 2	7.6	12.9	26.2	22.9	24.2	7.6
Reading 3	7.2	13.2	25.5	21.6	21.6	6.9
Reading 4	8.5	10.7	22.9	20.2	20.3	7.3
Reading 5	7.0	11.7	24.2	20.1	21.5	7.7
Average	7.5	12.2	25.1	21.4	22.1	7.7
Coefficient of Variation	0.58	0.08	0.06	0.06	0.07	0.09

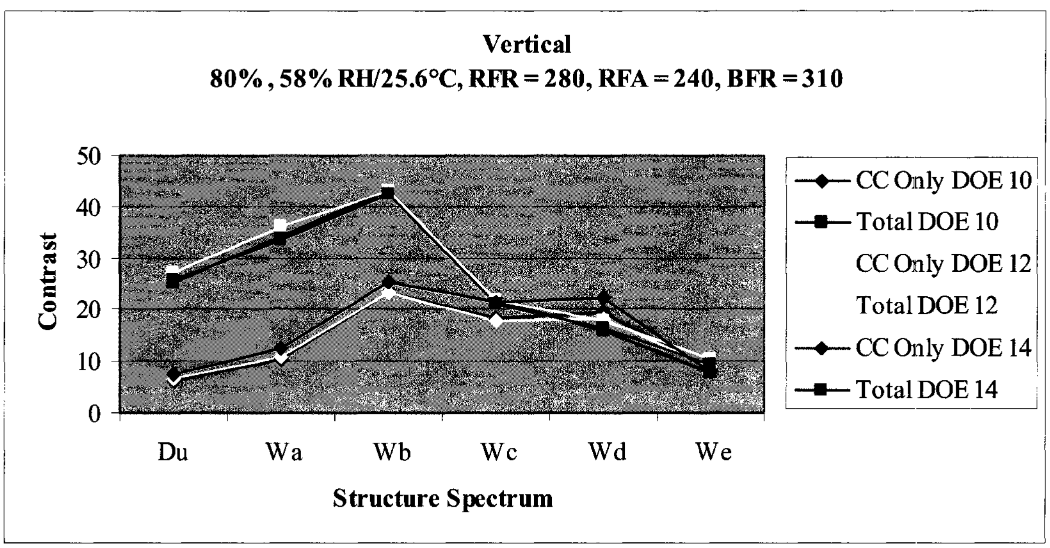
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.5	33.2	41.0	22.1	16.9	11.9
Reading 2	26.4	34.2	42.4	19.7	16.8	11.4
Reading 3	25.2	33.0	41.8	19.8	14.5	1.5
Reading 4	23.8	32.5	43.3	22.0	14.9	12.1
Reading 5	26.9	34.1	43.5	21.2	18.0	9.6
Average	25.6	33.4	42.4	21.0	16.2	9.3
Coefficient of Variation	1.20	0.02	0.02	0.06	0.09	0.48

Summary

H - CC	6.3	12.1	25.9	13.1	12.4	7.1
H - T	21.9	28.1	41.9	21.1	14.0	10.3
V - CC	7.5	12.2	25.1	21.4	22.1	7.7
V - T	25.6	33.4	42.4	21.0	16.2	9.3


Horizontal
80% , 58% RH/25.6°C, RFR = 280, RFA = 240, BFR = 260
50
40
30
20
10
0
Contrast
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 10
Total DOE 10
CC Only DOE 12
Total DOE 12
CC Only DOE 14
Total DOE 14


Vertical
80% , 58% RH/25.6°C, RFR = 280, RFA = 240, BFR = 310
50
40
30
20
10
0
Contrast
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 10
Total DOE 10
CC Only DOE 12
Total DOE 12
CC Only DOE 14
Total DOE 14

DOE 17

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	7.8	15.5	28.8	15.8	13.9	7.3
Reading 2	5.6	13.3	26.4	14.2	15.5	8.2
Reading 3	6.4	10.7	23.3	12.4	14.0	10.8
Reading 4	5.8	10.3	22.2	12.5	13.4	9.9
Reading 5	5.2	11.1	23.3	12.9	12.7	9.8
Average	6.2	12.2	24.8	13.6	13.9	9.2
Coefficient of Variation	1.01	0.18	0.11	0.11	0.07	0.15

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.5	30.3	44.7	22.2	15.1	7.3
Reading 2	20.7	31.2	43.5	21.0	15.9	9.7
Reading 3	19.5	27.7	42.0	21.1	15.1	9.5
Reading 4	17.6	25.4	40.8	19.8	12.5	9.2
Reading 5	18.4	24.8	39.3	20.3	12.2	8.6
Average	19.5	27.9	42.1	20.9	14.2	8.9
Coefficient of Variation	1.60	0.10	0.05	0.04	0.12	0.11

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.8	12.1	25.1	19.9	21.1	7.9
Reading 2	7.0	12.5	25.5	20.0	18.4	6.8
Reading 3	7.8	11.4	25.2	18.8	20.8	6.9
Reading 4	6.9	10.5	25.1	17.5	21.3	9.7
Reading 5	5.6	11.2	23.9	17.3	13.9	10.1
Average	6.8	11.5	25.0	18.7	19.1	8.3
Coefficient of Variation	0.79	0.07	0.02	0.07	0.16	0.19

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	25.9	36.1	43.5	22.8	20.8	7.4
Reading 2	25.8	36.3	39.1	21.4	21.1	8.3
Reading 3	25.7	32.9	40.1	22.4	20.6	7.2
Reading 4	23.1	31.5	42.2	21.5	17.5	6.5
Reading 5	23.7	34.7	42.3	23.1	18.3	10.4
Average	24.8	34.3	41.4	22.2	19.7	8.0
Coefficient of Variation	1.33	0.06	0.04	0.03	0.08	0.19

Summary

H - CC	6.2	12.2	24.8	13.6	13.9	9.2
H - T	19.5	27.9	42.1	20.9	14.2	8.9
V - CC	6.8	11.5	25.0	18.7	19.1	8.3
V - T	24.8	34.3	41.4	22.2	19.7	8.0

DOE 20

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	8.0	12.7	27.3	15.2	19.4	6.9
Reading 2	7.0	13.2	26.9	14.9	17.9	6.6
Reading 3	5.8	12.0	22.8	13.0	16.0	10.5
Reading 4	6.0	10.2	21.7	13.0	16.5	5.6
Reading 5	6.1	9.0	19.9	12.6	15.1	9.4
Average	6.6	11.4	23.7	13.7	17.0	7.8
Coefficient of Variation	0.92	0.15	0.14	0.09	0.10	0.26

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	21.3	30.7	42.7	20.0	15.7	9.1
Reading 2	21.8	28.2	39.0	19.9	16.9	13.2
Reading 3	20.4	26.6	37.8	18.7	17.7	6.3
Reading 4	18.8	24.6	37.1	17.2	15.5	11.2
Reading 5	18.5	24.5	40.3	16.7	12.5	9.7
Average	20.2	26.9	39.4	18.5	15.7	9.9
Coefficient of Variation	1.47	0.10	0.06	0.08	0.13	0.26

Vertical - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.2	8.9	21.0	18.4	17.7	7.7
Reading 2	5.6	9.3	21.7	17.7	16.6	5.8
Reading 3	5.7	10.4	24.2	17.1	18.7	4.3
Reading 4	5.3	9.5	19.9	15.3	17.3	7.8
Reading 5	4.3	9.1	21.5	15.0	15.1	9.1
Average	5.4	9.4	21.7	16.7	17.1	6.9
Coefficient of Variation	0.70	0.06	0.07	0.09	0.08	0.27

Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	24.2	32.7	40.7	21.2	17.7	14.5
Reading 2	25.1	33.6	41.7	21.4	20.8	10.9
Reading 3	22.8	34.9	41.5	20.8	19.1	9.1
Reading 4	23.6	31.3	39.8	20.1	19.2	8.3
Reading 5	24.0	33.6	41.8	22.2	17.6	7.6
Average	23.9	33.2	41.1	21.1	18.9	10.1
Coefficient of Variation	0.84	0.04	0.02	0.04	0.07	0.27

Summary

H - CC	6.6	11.4	23.7	13.7	17.0	7.8
H - T	20.2	26.9	39.4	18.5	15.7	9.9
V - CC	5.4	9.4	21.7	16.7	17.1	6.9
V - T	23.9	33.2	41.1	21.1	18.9	10.1

DOE 22

Horizontal - Clearcoat Only

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.4	11.5	22.5	12.8	12.2	5.3
Reading 2	6.3	9.7	20.8	11.2	12.6	8.7
Reading 3	4.7	7.6	18.5	9.3	9.1	7.1
Reading 4	4.9	8.2	20.5	10.3	10.0	11.2
Reading 5	6.1	8.5	19.8	10.9	12.6	5.9
Average	5.7	9.1	20.4	10.9	11.3	7.6
Coefficient of Variation	0.81	0.17	0.07	0.12	0.14	0.31

Horizontal - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	22.6	31.6	42.5	21.5	16.1	9.7
Reading 2	21.7	31.3	44.0	20.4	16.5	7.2
Reading 3	20.8	28.4	41.0	19.8	13.6	6.4
Reading 4	18.7	26.5	41.3	20.2	14.9	12.1
Reading 5	19.9	24.8	39.1	19.4	14.9	13.2
Average	20.7	28.5	41.6	20.3	15.2	9.7
Coefficient of Variation	1.52	0.10	0.04	0.04	0.08	0.30

Vertical - Clearcoat Only

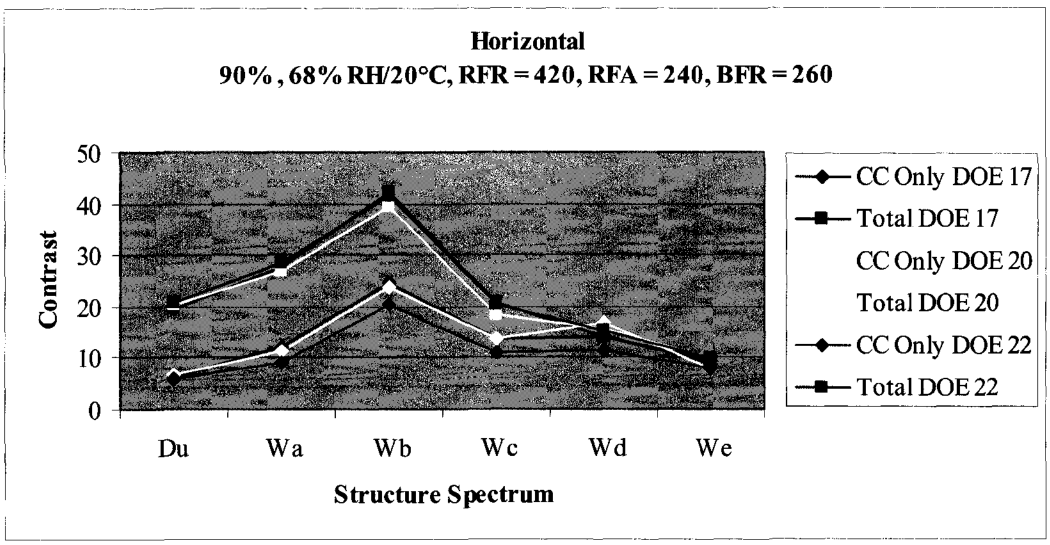
	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	6.8	11.6	25.6	24.7	23.0	11.1
Reading 2	7.3	11.5	26.4	24.7	23.1	5.5
Reading 3	6.7	11.5	26.3	23.4	22.8	7.1
Reading 4	6.5	11.0	25.1	19.7	20.7	8.1
Reading 5	6.3	9.7	23.2	19.2	19.3	9.7
Average	6.7	11.1	25.3	22.3	21.8	8.3
Coefficient of Variation	0.38	0.07	0.05	0.12	0.08	0.26

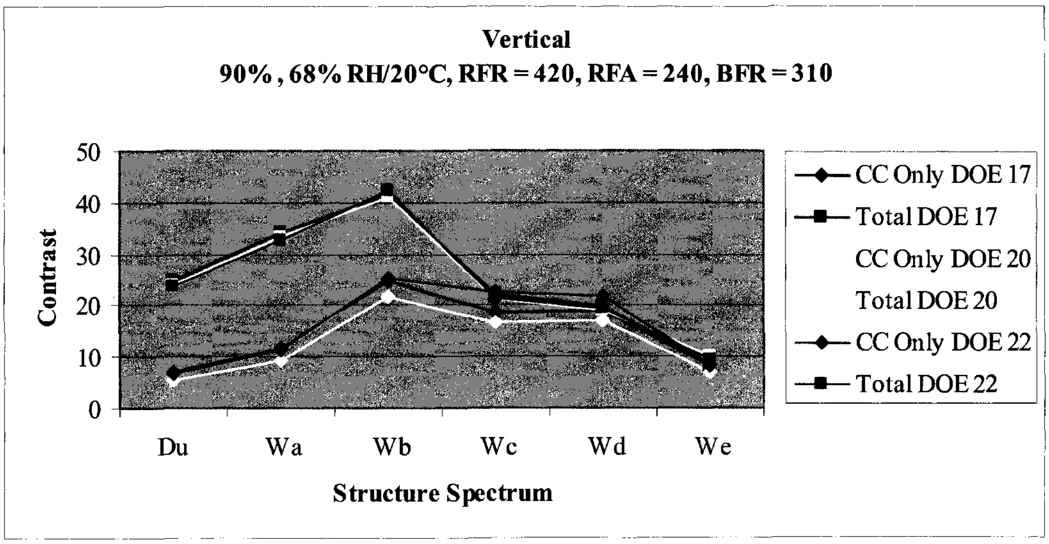
Vertical - Total

	Du	*Wa*	*Wb*	*Wc*	*Wd*	*We*
Reading 1	26.4	35.6	42.7	23.0	22.1	15.1
Reading 2	25.5	35.0	42.2	22.3	22.5	6.7
Reading 3	23.1	33.4	44.0	22.3	15.8	9.5
Reading 4	22.6	30.0	41.4	19.8	17.9	7.7
Reading 5	21.5	29.2	41.9	18.6	17.9	7.7
Average	23.8	32.6	42.4	21.2	19.2	9.3
Coefficient of Variation	2.05	0.09	0.02	0.09	0.15	0.36

Summary

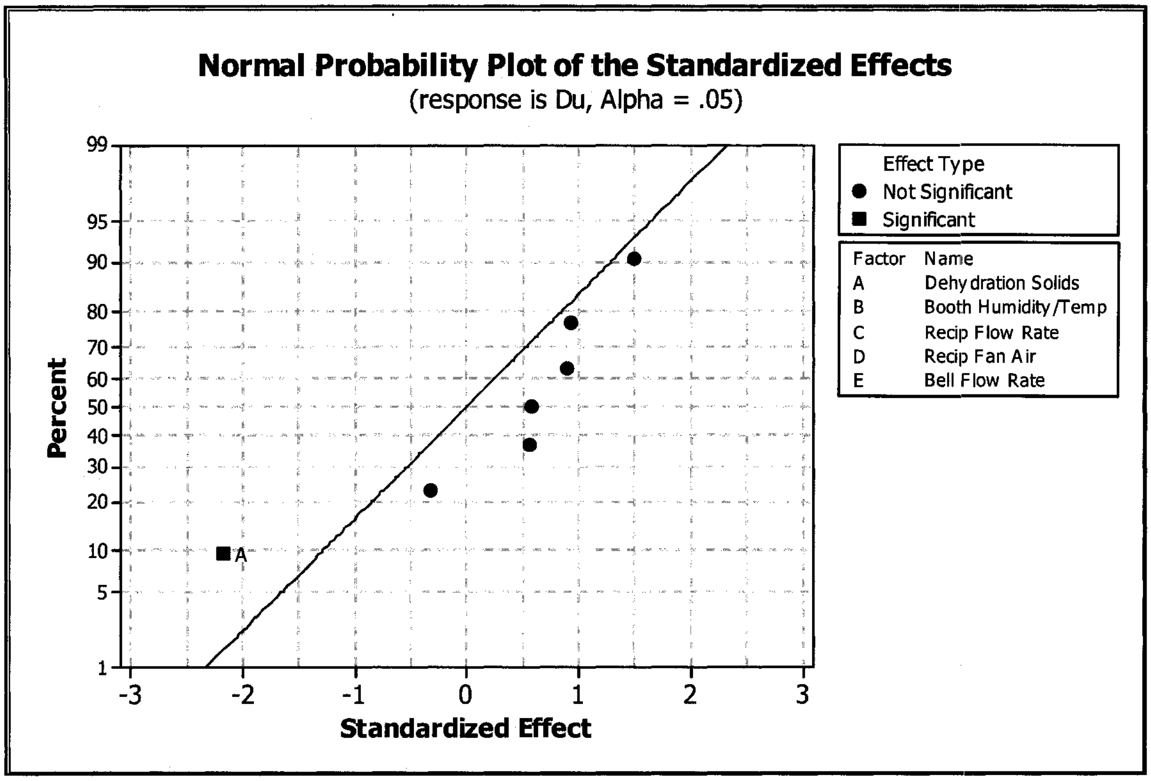
H - CC	5.7	9.1	20.4	10.9	11.3	7.6
H - T	20.7	28.5	41.6	20.3	15.2	9.7
V - CC	6.7	11.1	25.3	22.3	21.8	8.3
V - T	23.8	32.6	42.4	21.2	19.2	9.3

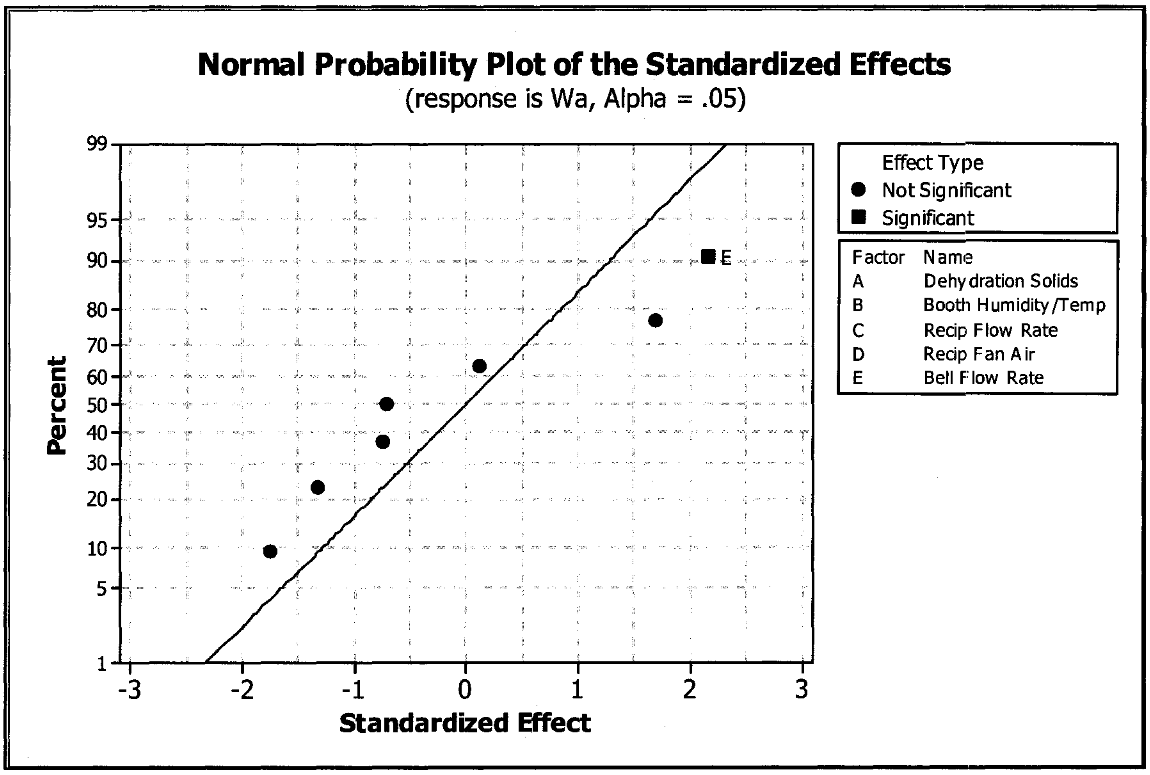

Horizontal
90%, 68% RH/20°C, RFR = 420, RFA = 240, BFR = 260
Contrast
0
10
20
30
40
50
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 17
Total DOE 17
CC Only DOE 20
Total DOE 20
CC Only DOE 22
Total DOE 22


Vertical
90%, 68% RH/20°C, RFR = 420, RFA = 240, BFR = 310
Contrast
0
10
20
30
40
50
Du
Wa
Wb
Wc
Wd
We
Structure Spectrum
CC Only DOE 17
Total DOE 17
CC Only DOE 20
Total DOE 20
CC Only DOE 22
Total DOE 22

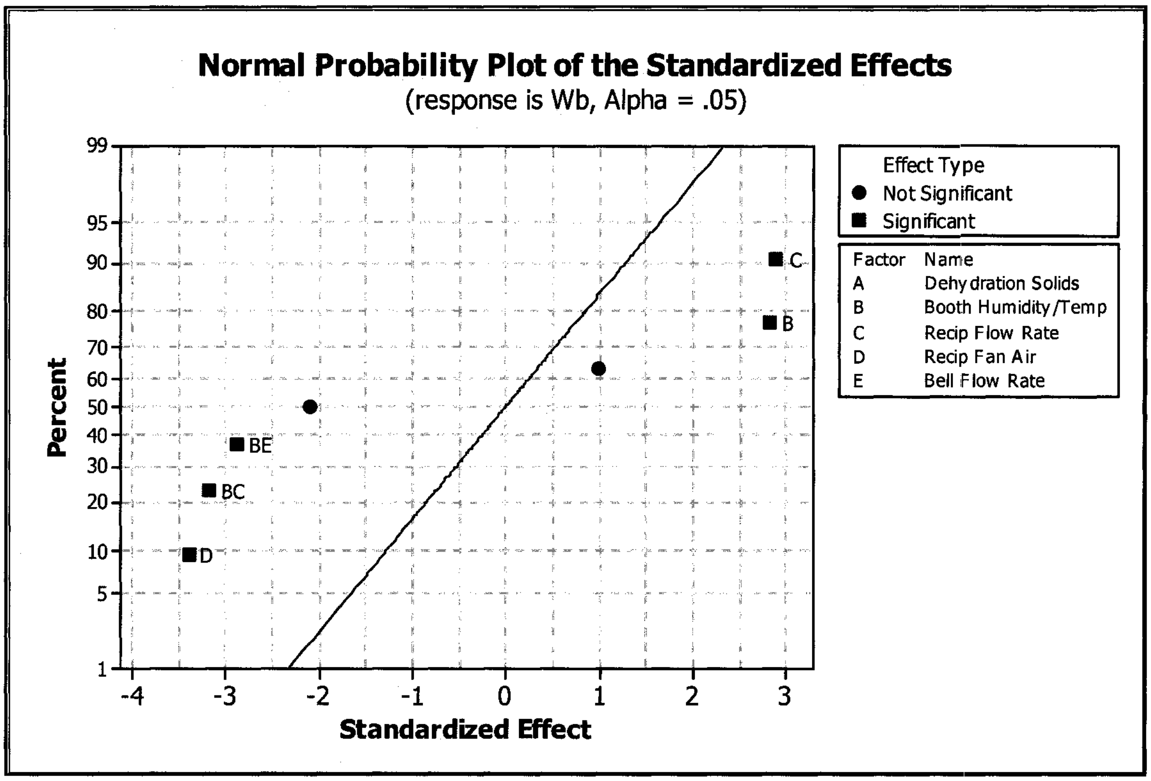
APPENDIX K – NORMAL PROBABILITY PLOT RESULTS

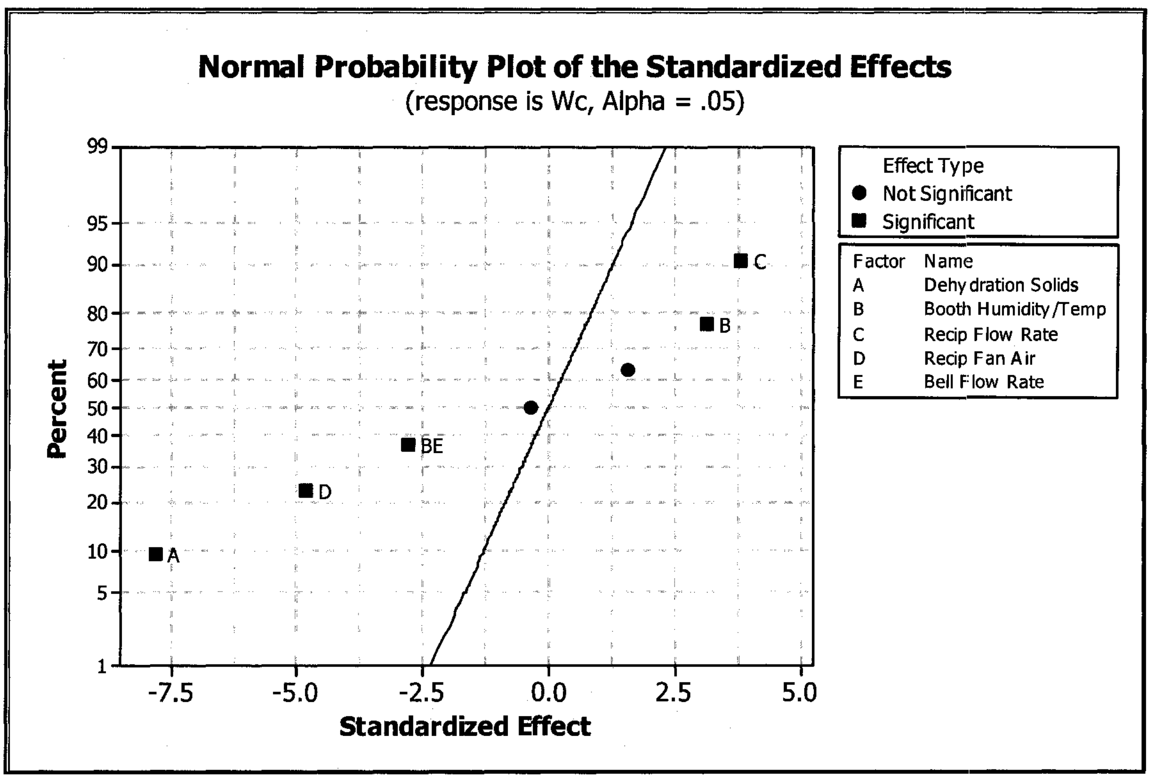
Normal Probability Plot – Base Coat + Clear Coat Horizontal Panels



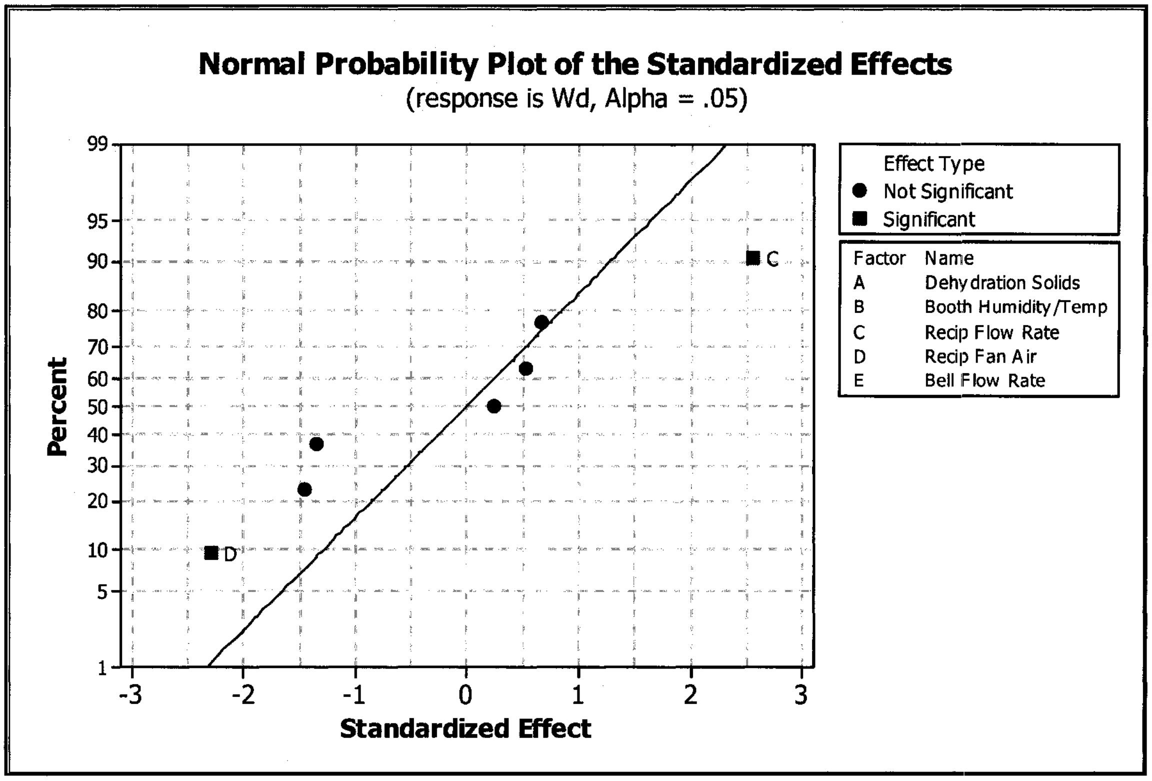


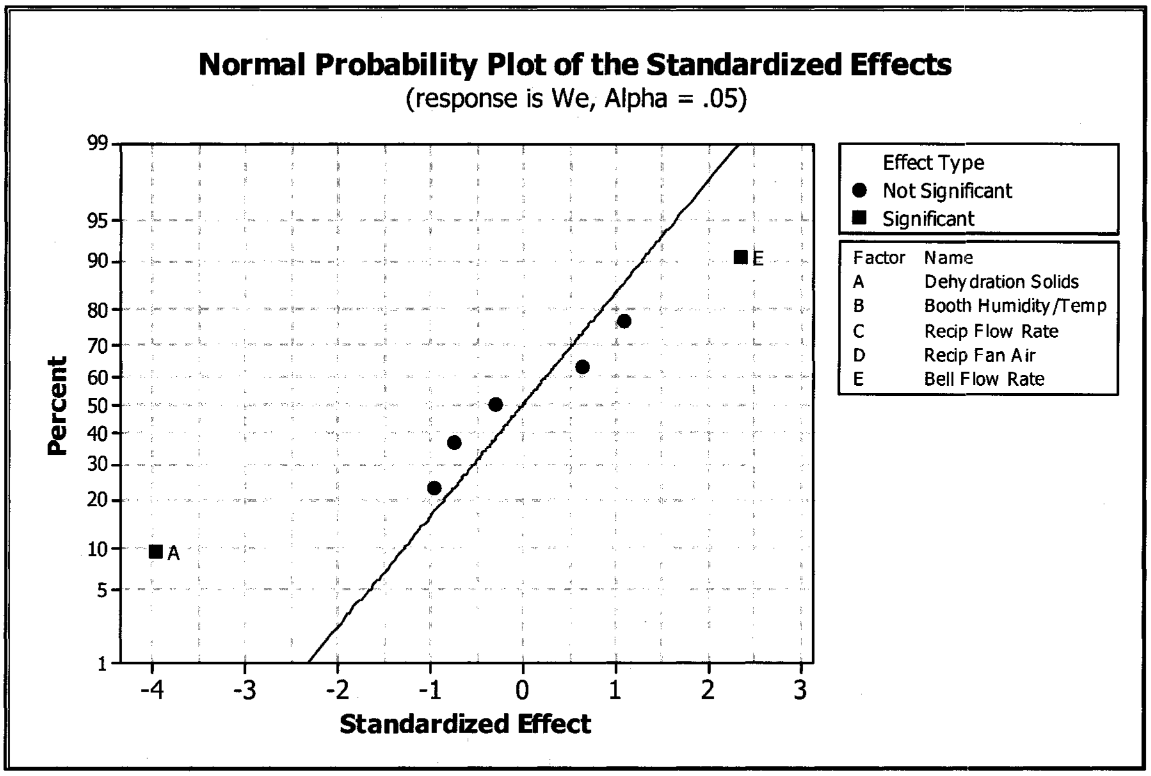
Normal Probability Plot – Base Coat + Clear Coat Horizontal Panels



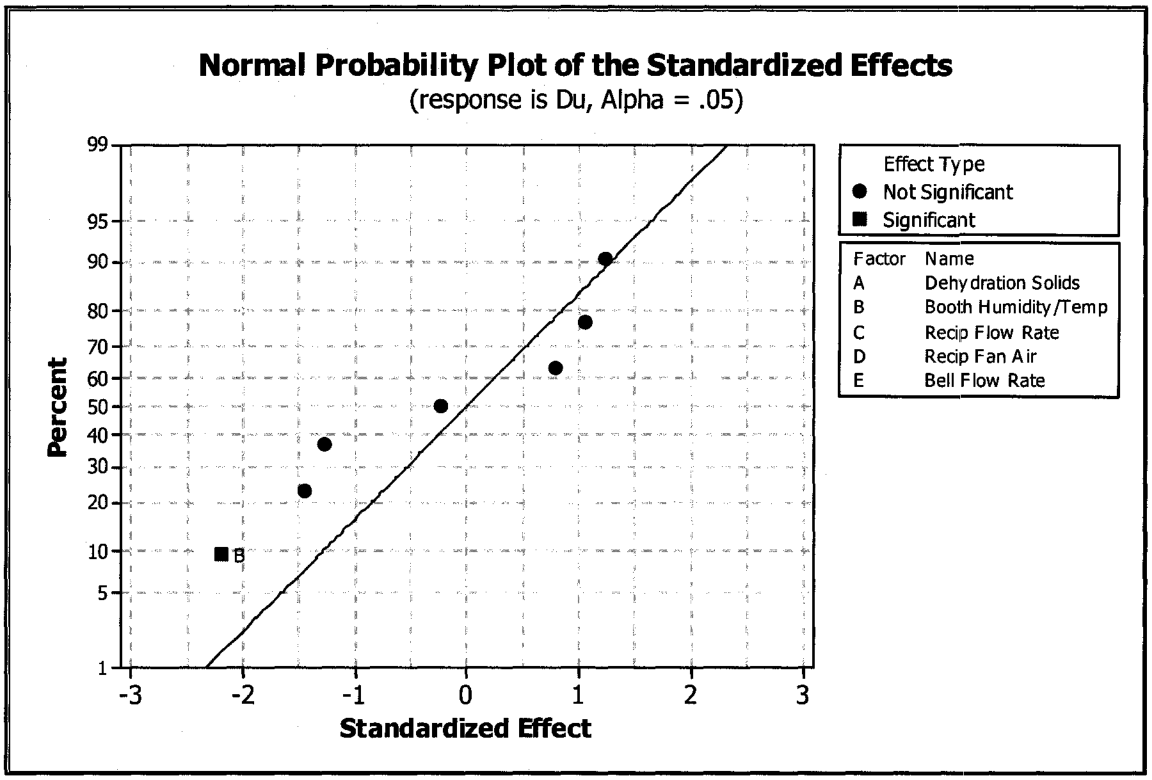


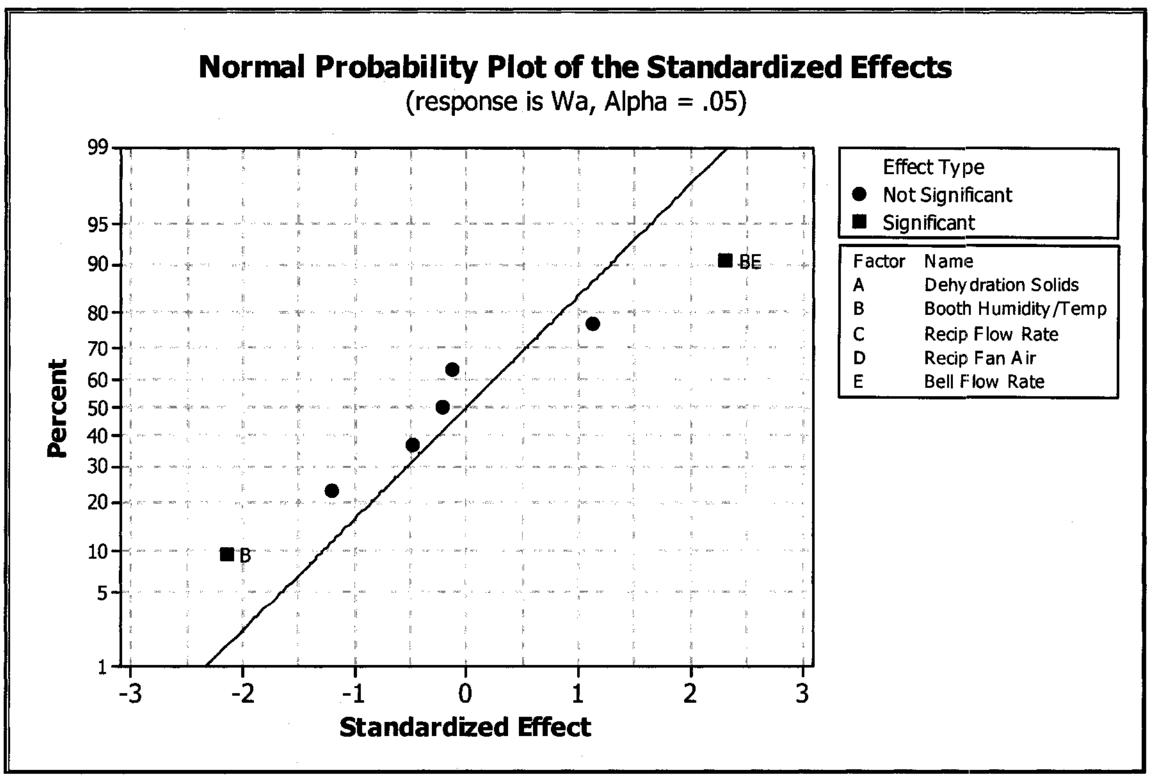
Normal Probability Plot – Base Coat + Clear Coat Horizontal Panels



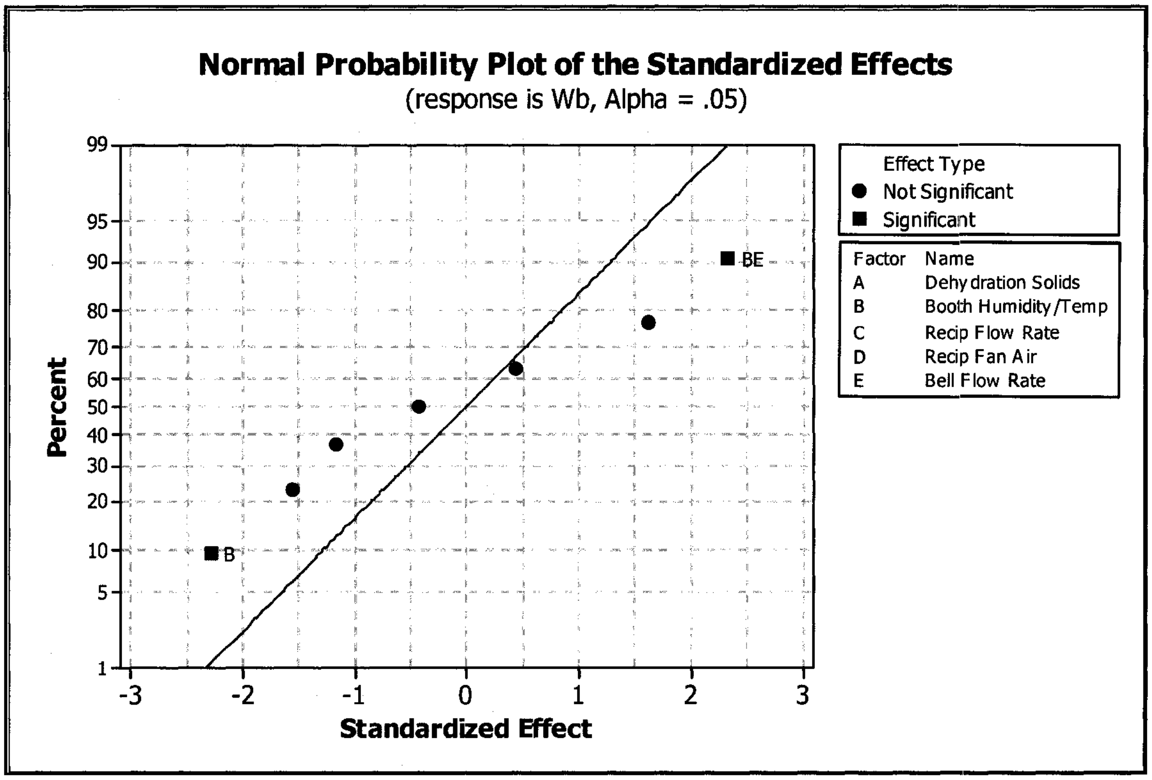


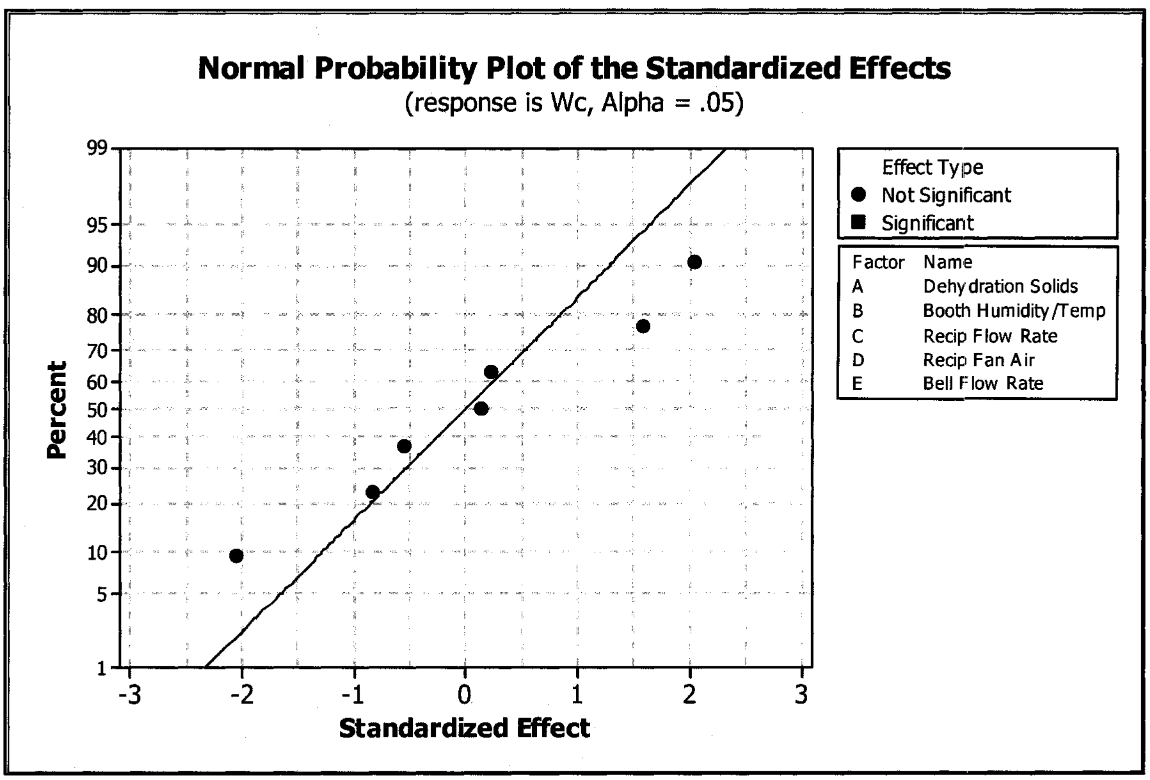
Normal Probability Plot – Clear Coat Only Horizontal Panels



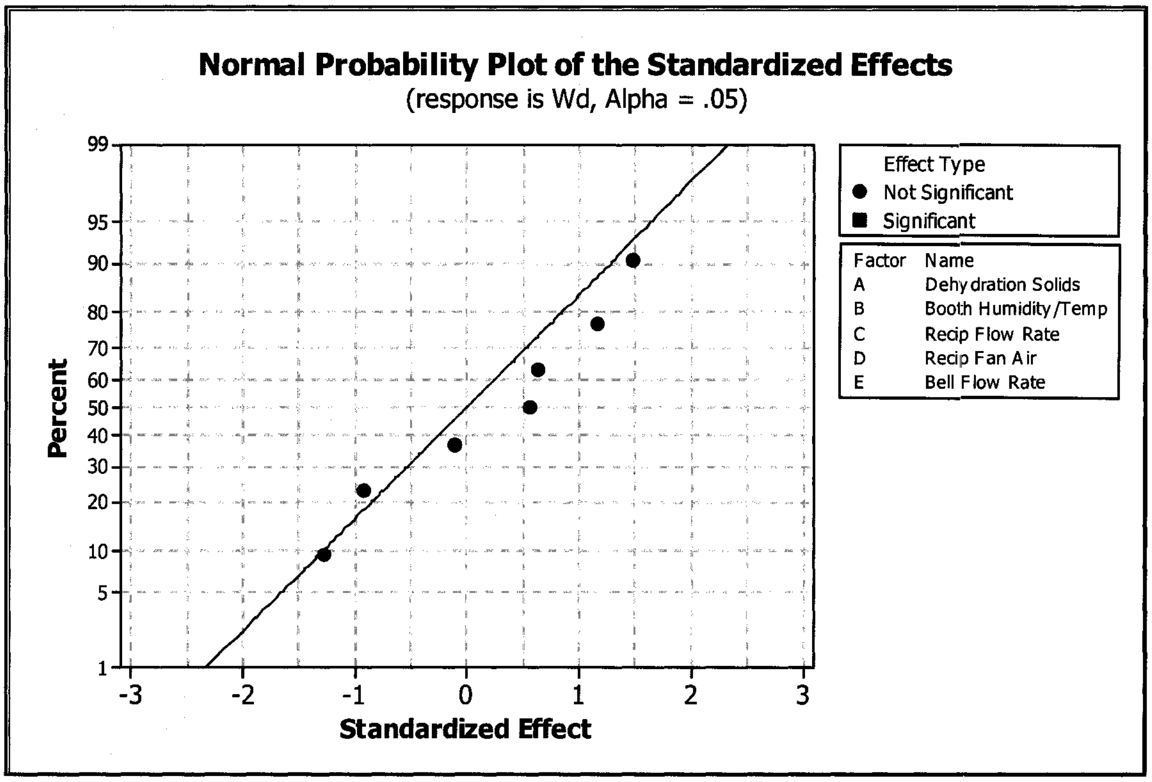


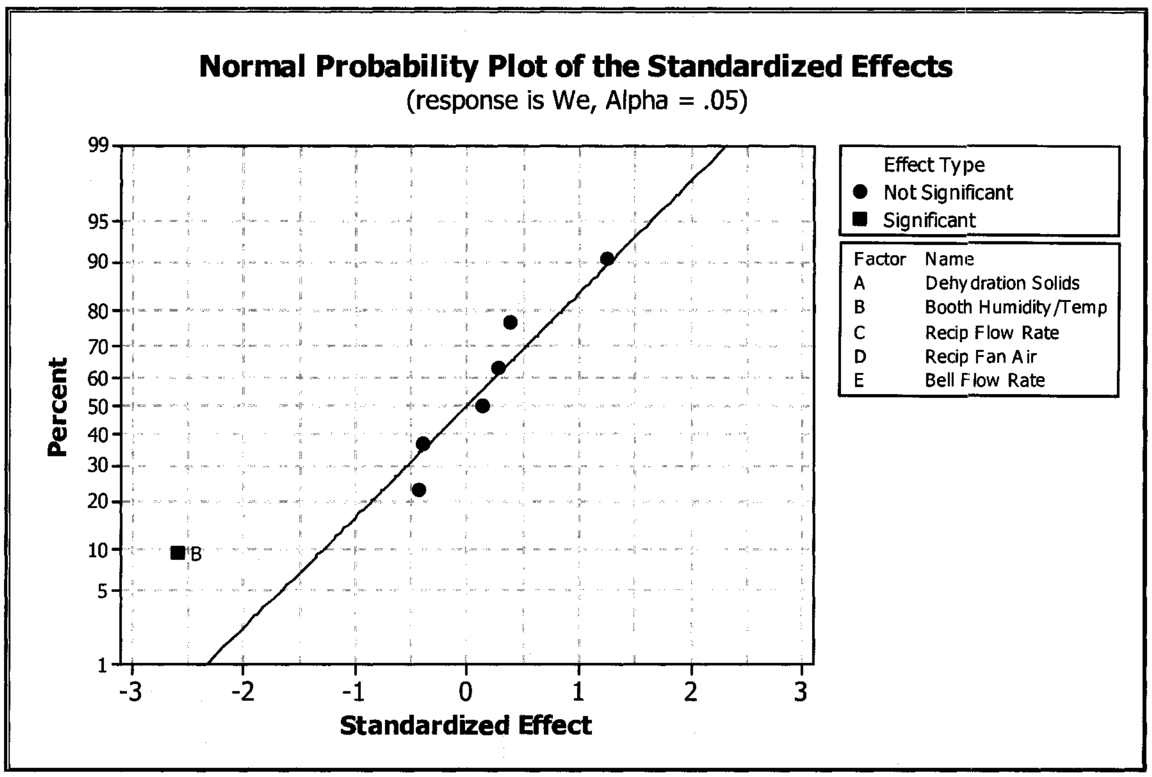
Normal Probability Plot – Clear Coat Only Horizontal Panels



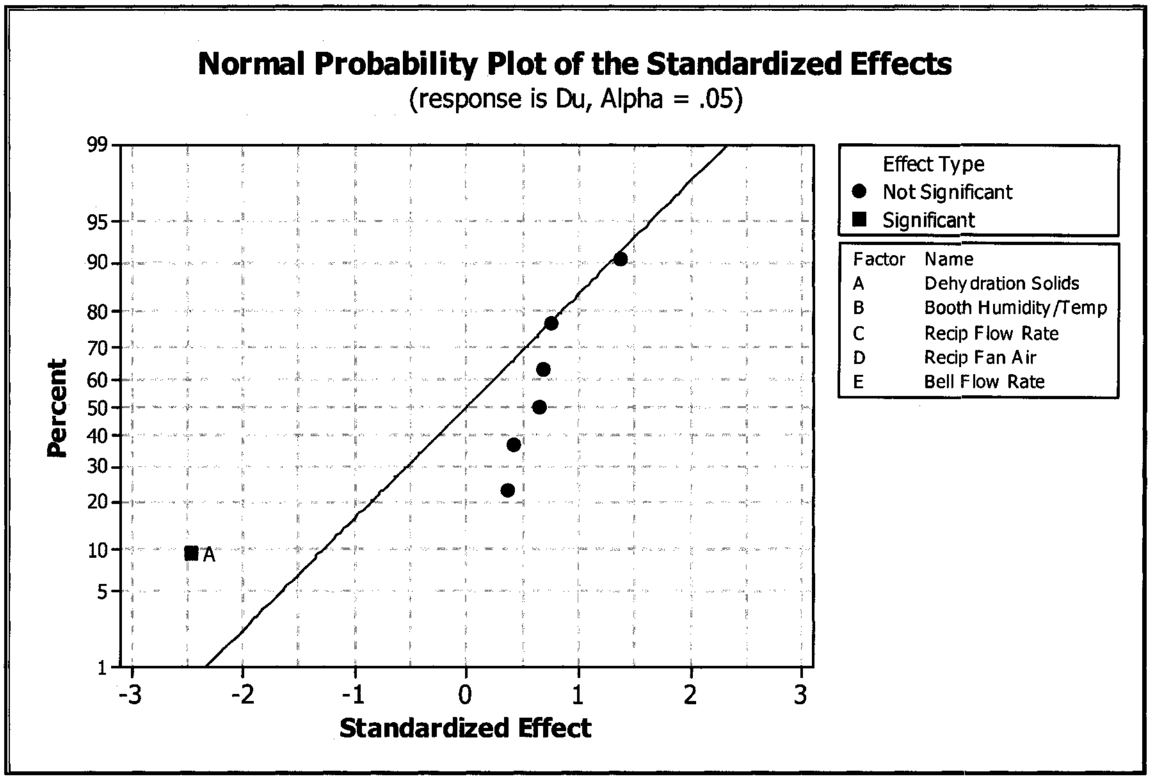


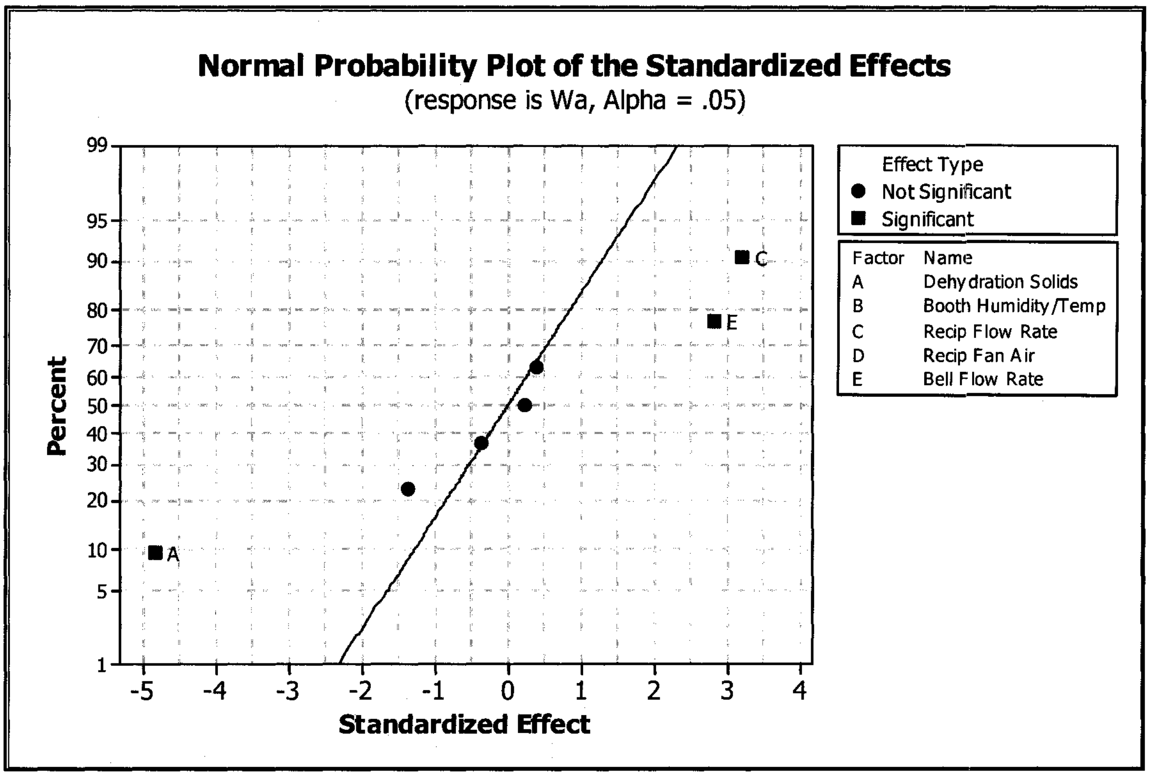
Normal Probability Plot – Clear Coat Only Horizontal Panels



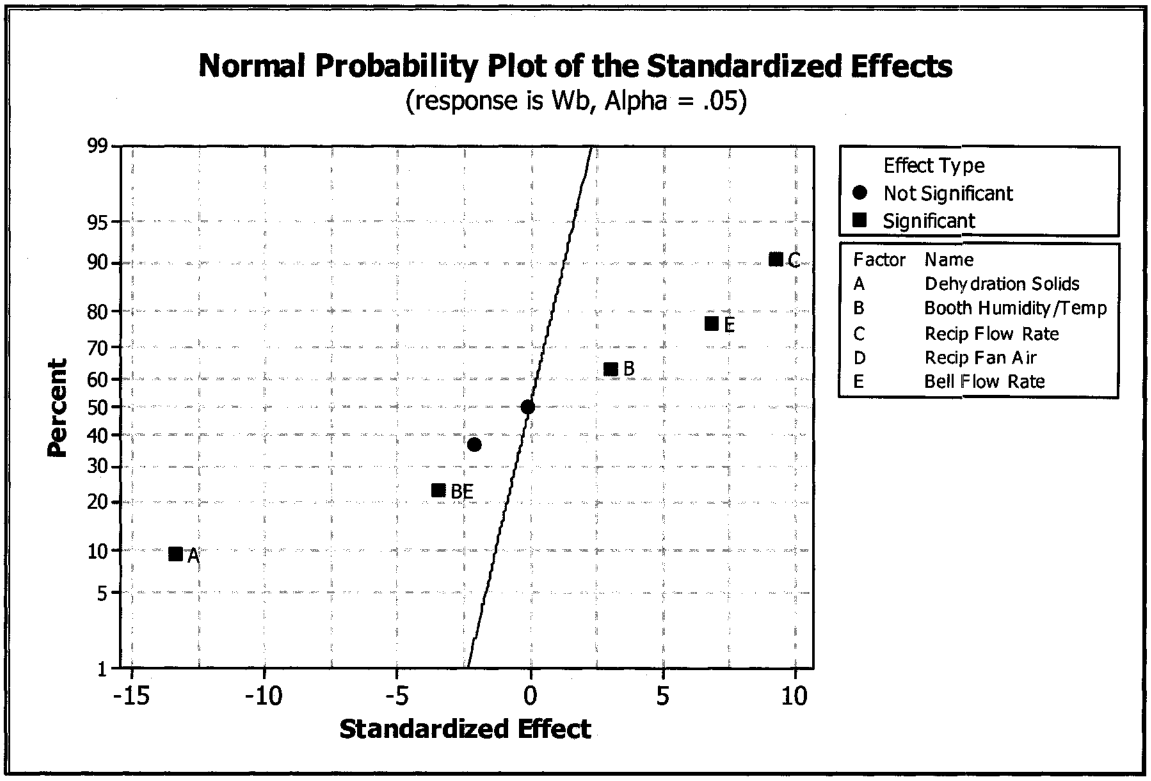


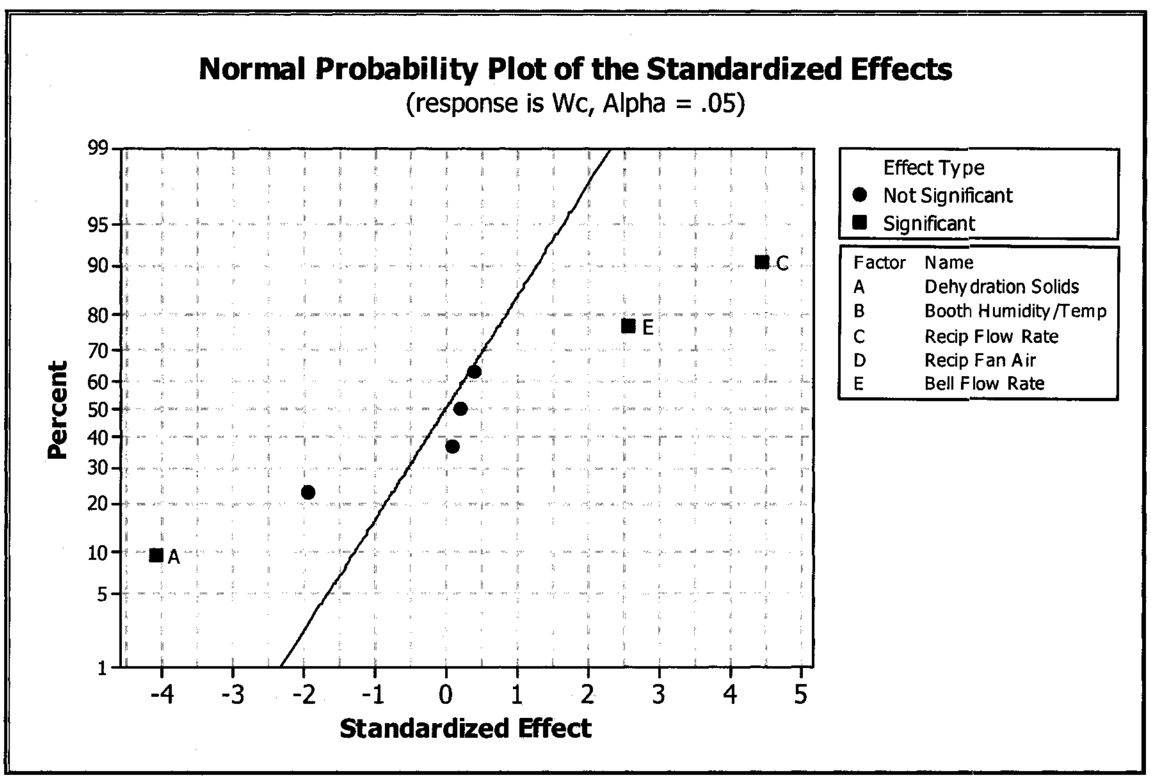
Normal Probability Plot – Base Coat + Clear Coat Vertical Panels



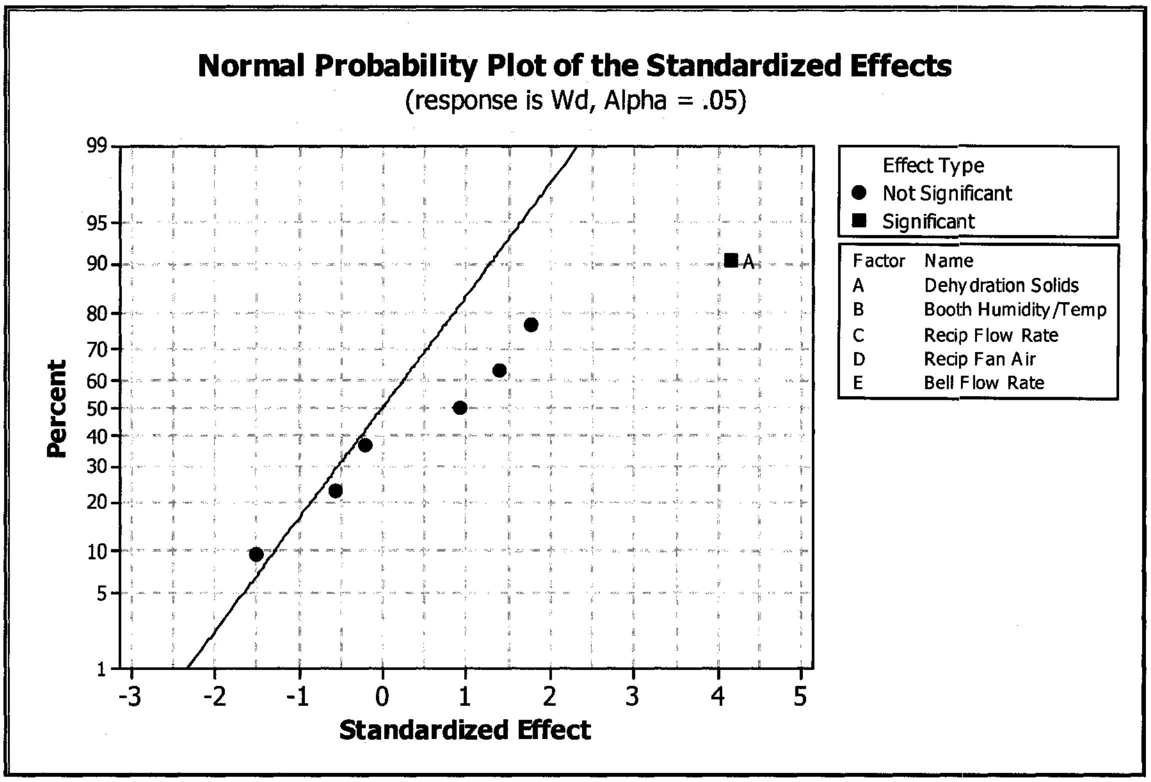


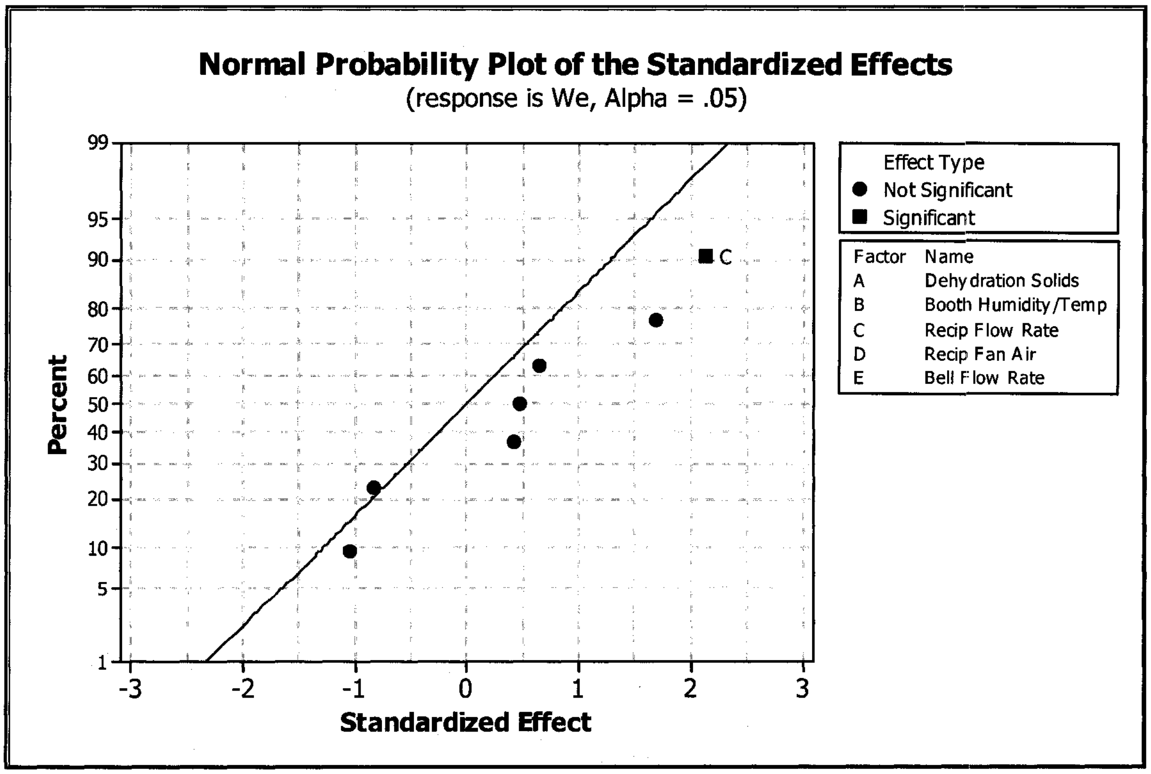
Normal Probability Plot – Base Coat + Clear Coat Vertical Panels



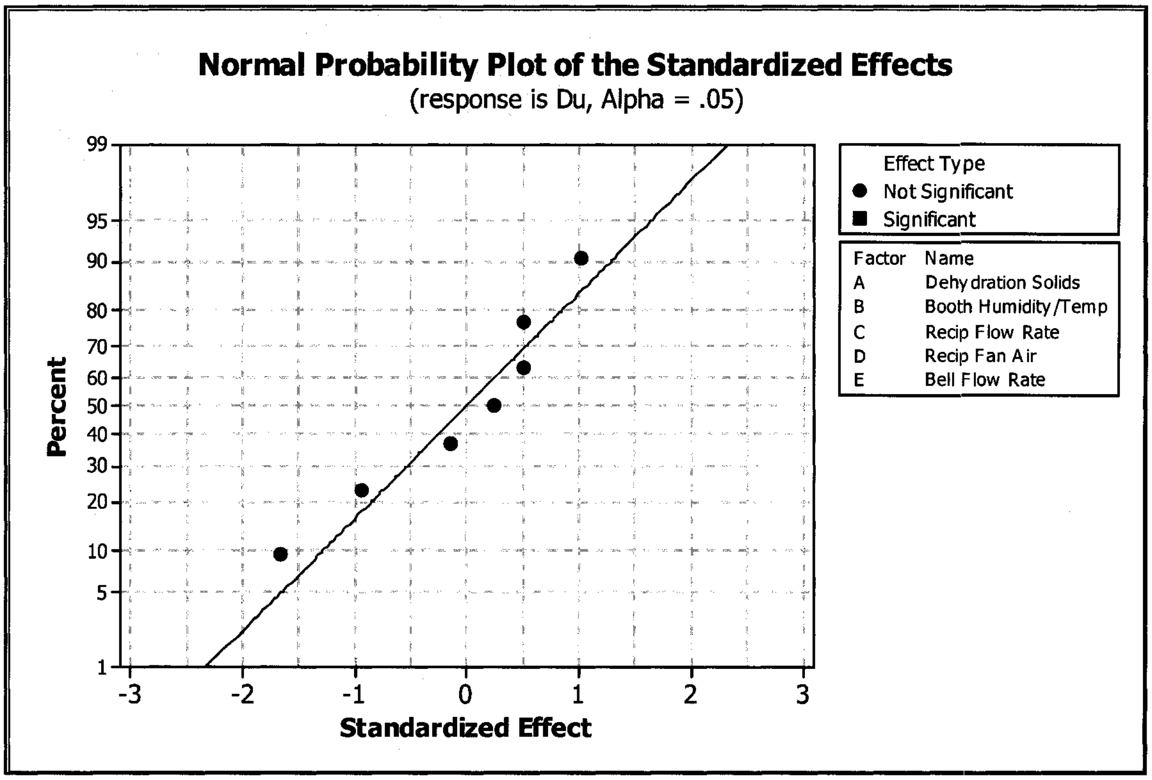


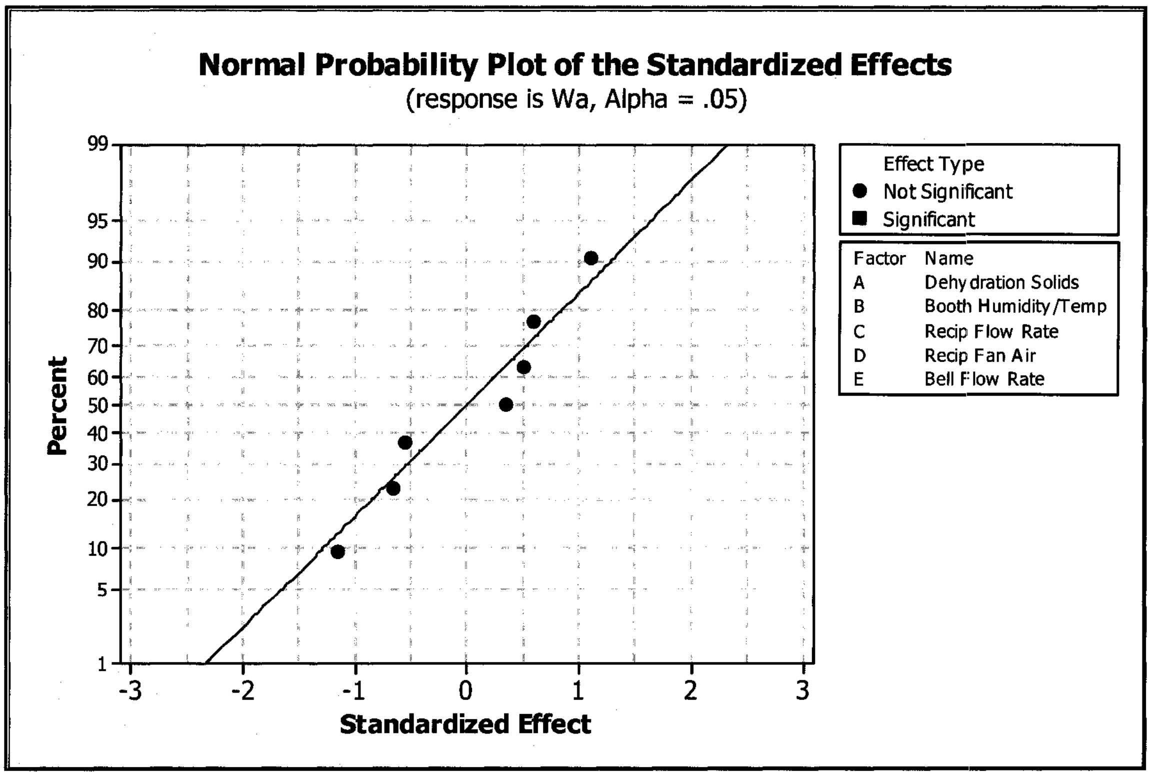
Normal Probability Plot – Base Coat + Clear Coat Vertical Panels



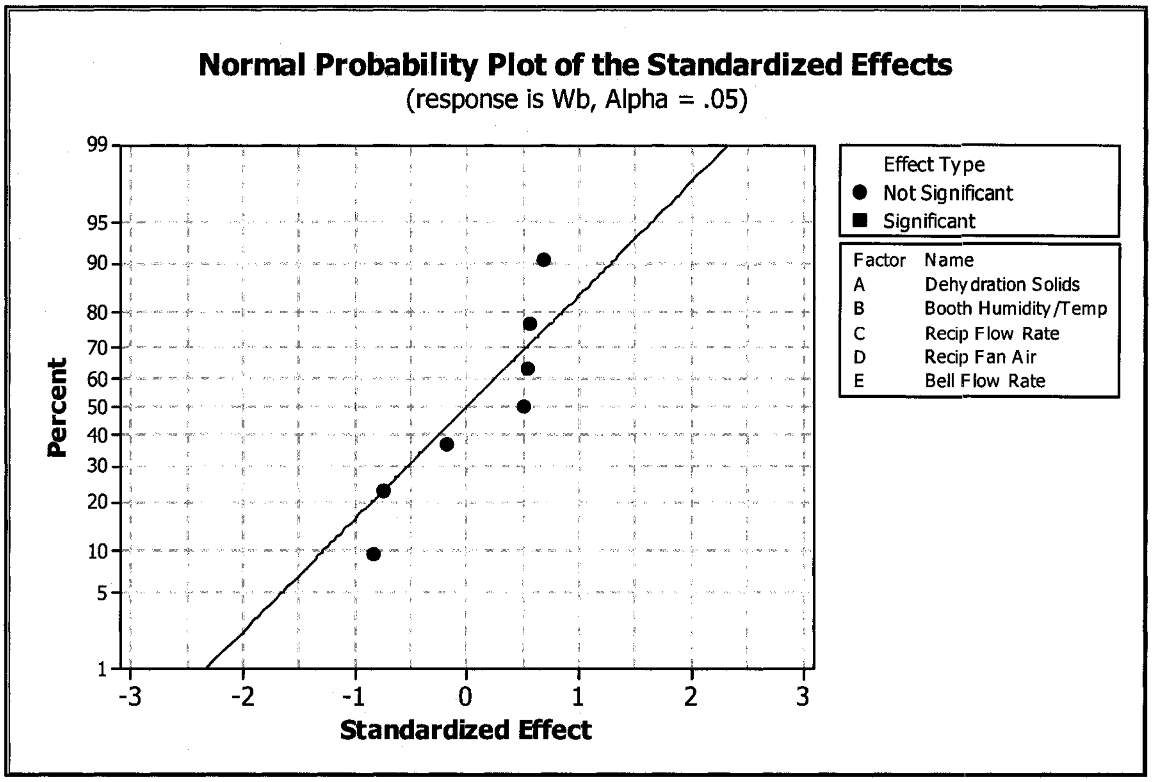


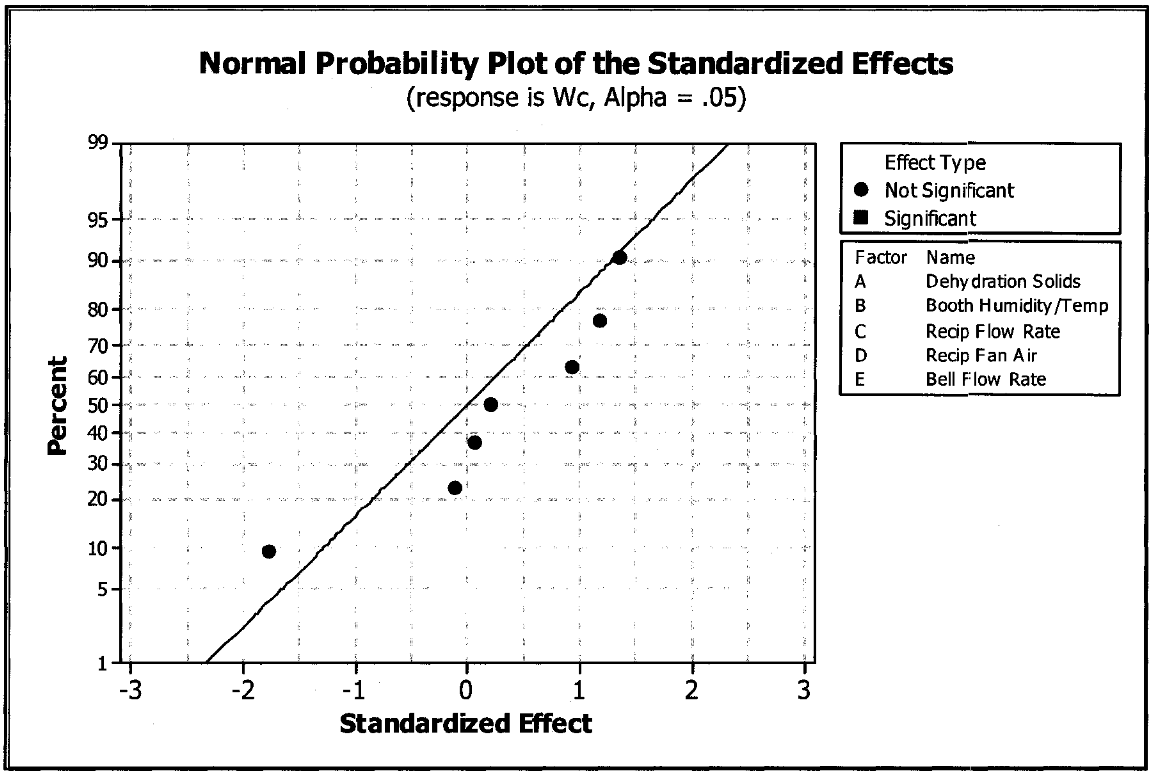
Normal Probability Plot – Clear Coat Only Vertical Panels



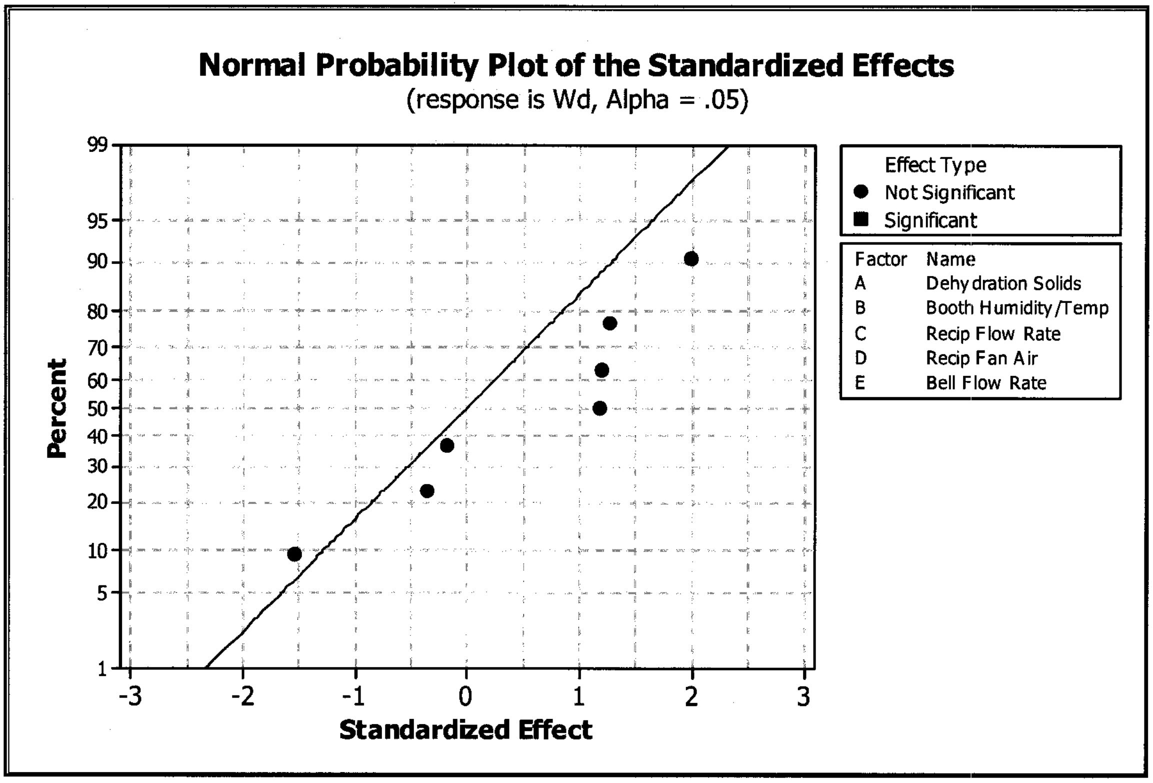


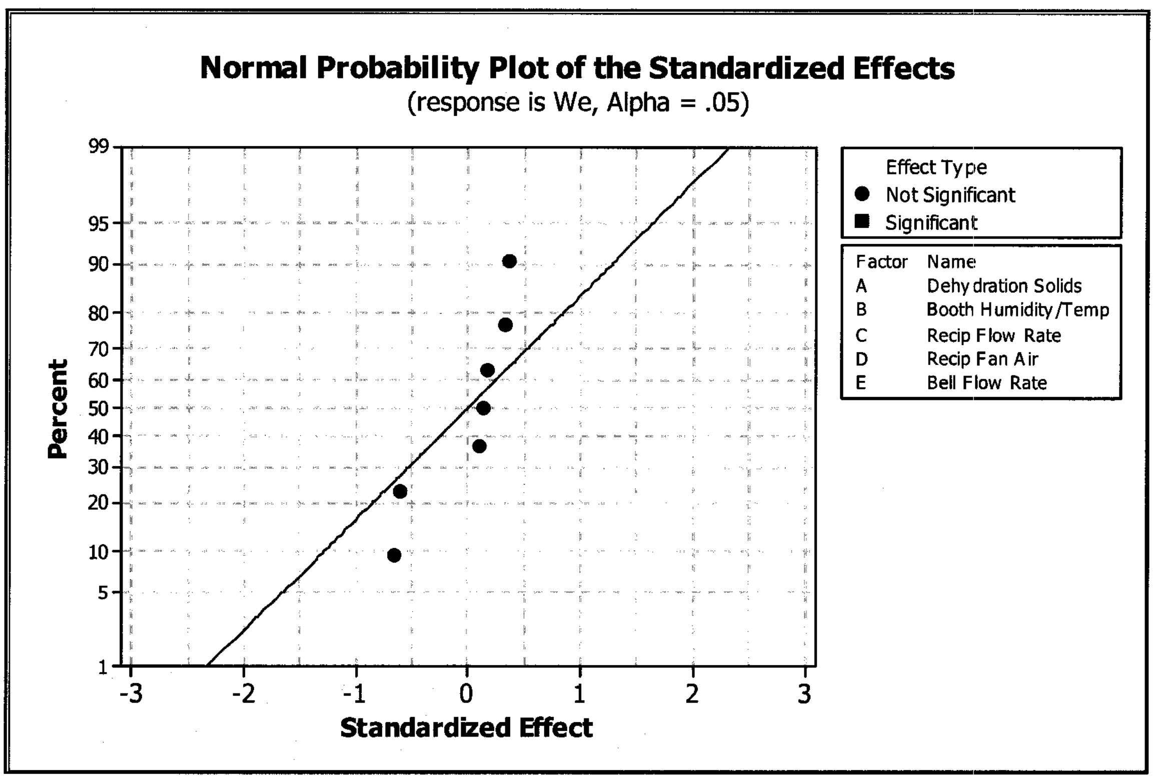
Normal Probability Plot – Clear Coat Only Vertical Panels





Normal Probability Plot – Clear Coat Only Vertical Panels





APPENDIX L – COPYRIGHT RELEASES

VITA AUCTORIS

Jennifer Lynn Giroux was born in Windsor, Ontario, Canada on July 11, 1981. She graduated from St. Anne's High School in May 2000 and enrolled in the engineering program at the University of Windsor. She graduated with a Bachelor of Applied Science, concentration in Environmental Engineering. Upon graduation, Jennifer obtained a position with DaimlerChrysler Canada in the Automotive Coatings Research Facility. She enrolled in the Faculty of Engineering to pursue a Master of Applied Science degree. Jennifer's interests include relating qualitative appearance data to quantitative instrumentation and optimizing the paint process through correlation of appearance to process.